TEE BEAM MANUFACTURING ANALYSIS

FOR

WEIGHT REDUCTION AND PRODUCIBILITY

NSRP PROJECT #N7-91-4

FINAL REPORT

PRESENTED TO:

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October 31I, 1994

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE **31 OCT 1994**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **TEE Beam Manufacturing Analysis for Weight Reduction and Producibility**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Surface Warfare Center CD Code 2230 - Design Integration Tools Bldg 192 Room 128 9500 MacArthur Blvd Bethesda, MD 20817-5700**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**124**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

ACKNOWLEDGMENTS

This project was funded by the National Shipbuilding Research Program. The author is indebted to all who had the foresight and the courage to develop and continue the funding for the program, and to those whose continued participation and guidance have helped to make work. Further thanks are expressed to Jim Rogness, Doug Diedrick, and John Meacham of Peterson Builders, Inc., SP-7 program managers during the life of this project, for guidance and support.

The author gratefully acknowledges the help, guidance and other contributions of many persons and organizations throughout the period of this study. Most of the organizations listed below provided open time on equipment at their facilities to perform work for this project. With apologies to any which may have been overlooked, 1 am especially indebted to:

Paul Denney, Eric Whitney, Jim McDermott, Russ Knee, and Bill Rhodes of The Applied Research Laboratory at Pennsylvania State University, State College, PA.

Dana Elza of Coherent General (now Convergent Technologies), Sturbridge, MA.

Kerry Pulaski of Thermal Dynamics, Inc., West Lebanon, NH.

Robert Ulrich of Laser Applications Incorporated, Westminster, MD.

David Veverka, Tarsem Jutla, Harvey Castner, and many others at Edison Welding Institute, Columbus, OH.

Tom Renchko of Stardyne, Inc., Johnstown, PA.

Tim Webber and Mark Kline of Hobart Laser Products, Livermore, CA.

Steve Maddox, Steve Riches, Rich Leggett and many other of The Welding Institute, Abington, Cambridge, U.K.

David Katula and the T-bar Stripping Crew at the Hardings Facility of Bath Iron Works.

And for expert guidance and continued support: David Forrest, Chief Welding Engineer, Bath Iron Works Corporation, Bath, Maine.

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I. ABSTRACT

This report analyzes the manufacturing of tee shapes for stiffening ship structure. Tees produced by the traditional method of deflanging hot-rolled I-beams (I/T shapes) have been compared to fabricated tee-shapes produced from plate for a target group of 1700 tees used in a DDG-51 class vessel. A review of design considerations for several structures has showed that weight savings averaging 18% were possible while still maintaining strength. To produce a DDG, flanges must be stripped from I-beams totaling more than 690 tons [of 2240 pounds] in weight, producing some 170 tons of scrap, a material loss of 25%, easily in excess of $90,000. Given that weight and cost savings are possible by converting UT shapes to fabricated tees, an evaluation of methods to produce tee sections was undertaken. Both fabricating and stripping methods were considered, including newer technologies such as plasma cutting and laser cutting and welding. Mock-up testing was performed using several candidate technologies and the results compared. Plasma-arc cutting reduced distortion on forty-foot test beams by 50% compared to oxyfuel methods. Economic analysis revealed that fabricated tees were less costly to produce than deflanged I-beams, and that handling functions were the greatest cost element of the traditional oxyfuel cutting methodology.

II. INTRODUCTION AND SCOPE

This program was undertaken to compare the relative merits of various schemes for producing panel stiffeners, considering design aspects of fabricated tees versus those stripped from I-beams, and evaluating various methods of producing tee shapes, considering current as well as new technologies. Although fabricated tees may offer some benefits, it is not a foregone conclusion that fabrication is the best approach for every situation. Thus, both stripping and welding methods have been considered, as well as the quality and relative economies offerd by the various processes.

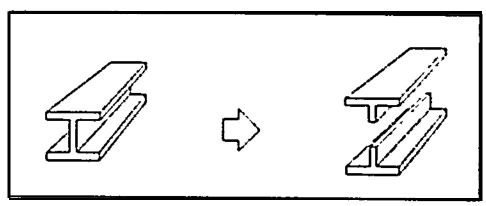


Figure 1. Split I-beam

Most ship designs have required tee shapes for stiffening panels (decks, shells, and bulkheads). Typical mill practice of splitting I-beams down the center of the web (e.g., a 12-inch deep I is split into two 6-inch tees, as in Figure 1.) does not provide a shape with the best section properties for ship panel stiffening. This is in large measure due to the optimization of I-shapes for building construction, by far the largest consumer of these shapes. A convenient solution has been the traditional approach of removing one pair of flanges, so that the 12-inch I becomes a 12-inch tee. This yields a section with adequate properties for ship panel stiffening, and provides a readily available source of material of convenient length for processing. Although this requires minimal labor input on the part of the shipyards, it produces a significant amount of scrap material. Current production methods frequently result in distortion or damage to the members.

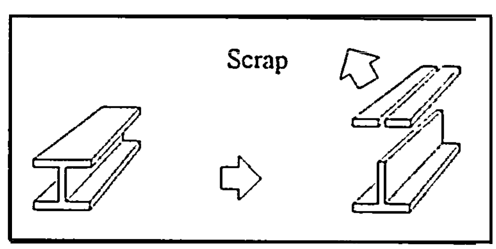


Figure 2. Stripped I-beam

Since the design process can yield values for section properties (the “design shape”) which are not necessarily exactly those of a section available from steel producers, the "next larger" available shape is chosen from the catalog. Flange and web thicknesses and widths of available shapes may also be disproportionate to those of the design shapes. Thus, the convenience of selecting from a catalog results in greater weight and cost. The alternative is to design a shape to be built from plate. Plausibly, plate material is available in a greater range of thicknesses, so that a fabricated tee section could be made with dimensions conforming more closely to those of the design shape. Furthermore, material thickness could be more efficiently used to more nearly match the section properties of the design shape, instead of using flange and web thickness ratios which suit rolling mill production of I-beams.

The fabricating of tees from plate is not at all new or unique,[1,2,3,4,5] but has been limited to the extremes: production of tee sections where the section size or shape is not available as a hot-rolled I-beam, especially in the case of deep frames and web frames, or in the case of extremely lightweight sections. Usually, mid-range sections have not been considered cost-effective for custom production. There can be several reasons for this, especially when shipyard hand-fit and manual or semiautomatic welding methods are used:

- A wide variety would be needed, with little repetition of specific designs,
- Designing of custom shapes adds time to the design phase of the ship,
- Estimated yard labor costs are typically high, compared to steel costs,
- Traditional fit-up and alignment of flange to web is viewed as diffllicult, especially for 50-foot sections, and
- Significant distortion is produced by semiautomatic welding methods, with high rework costs for postweld straightening.

Newer welding technologies, such as laser welding and high-frequency resistance welding[6,7] have challenged these assumptions, and mechanized equipment for producing tees has been continuously improved, but neither have made significant inroads into shipbuilding practice The increasing degree of mechanization of nearly all shipyard processes will have a significant impact on the decision process in the future, but probably the biggest single contributor to progress in this area will be the wider implementation of CIM throughout shipyards.[8]

III. PROBLEM STATEMENT

I-beam stripping is typically done using the dual-torch Oxy-Fuel Cutting (OFC) process, with some sort of mechanized gantry or other device to move the torches over the beams. In the process, 25% of purchased material is turned into scrap. While OFC equipment is simple and reliable, the process often causes damage to the tees. Figure 3 shows some examples which may require rework, such as camber distortion, and damage to webs due to errors in torch tracking. Excessive offset occurs when torches are moved away from the web to avoid damage. Offset leaves excess weight, and makes welding of the tee shape to the panel more difficult, especially when mechanized panel line equipment is used

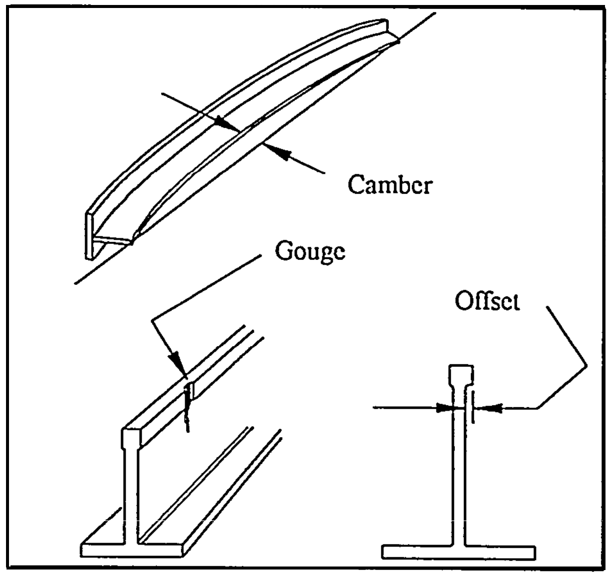


Figure 3. Problems in OFC Deflanging

Beyond the problems encountered in making tees from I-beams, there are other aspects of hot-rolled shapes which should be evaluated. The most common manufacturing specification governing dimensional tolerances of hot-rolled I-beams is ASTM A-6.[26] In some cases, this standard allows dimensional variations which can exceed those of the fabrication documents for ship hulls. Figure 4 shows two cases: webs may be offset so far as to fail to line up at all, and section depth may vary to the extent that flanges are offset by an amount greater than their thickness. Often, these conditions are not discovered until major structural units are being joined to each other. Rework of some kind is usually required at this stage.

Furthermore, the use of I/T shapes may induce a weight penalty on the vessel design, whereas a fabricated shape may offer needed properties at reduced weight. The design review phase of this project established that tee shapes designed to specified loading requirements would weigh an average of 18% less than the I/T shapes currently available. Unfortunately, design specifications may not allow shipbuilders to take full advantage of these weight savings. The DDG-51 detailed specifications, for instance, allow the substitution of fabricated shapes for I/T shapes only if the built-up tees are identical in section to the hot-rolled I/T's they replace.[30] Beyond that, surveys of as-received hot-rolled shapes have shown that product weight exceeds theoretical weight by 4-5%. Plate, on the other hand, has consistently shown

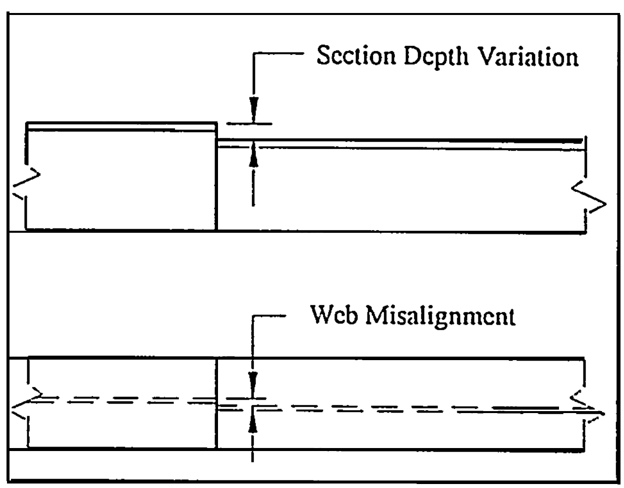
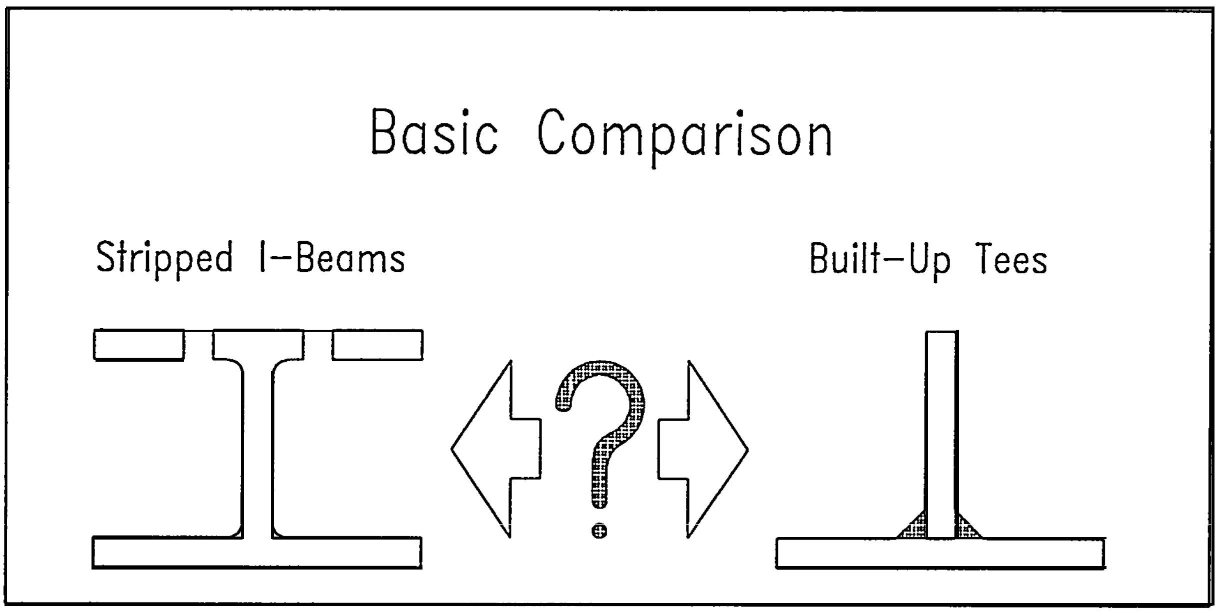


Figure 4. Some Variations Allowed by A-6

closer compliance, and is now available at competitive prices from several sources with weight only varying by 1% or less from theoretical.

Finally, welding methods may be more cost-efficient than burning methods, depending on the technology used, and the equipment to apply it. Welding web and flange together allows the tees to be built to exact design, with the welds sized to meet exact loading and service requirements of the stiffened structure. Welding also offers greater flexibility in choice of materials, so that material properties such as strength, impact tolerance, and corrosion resistance can be tailored to meet the demands of the vessel.

The problem becomes one of overall strategy in determining how structures should be stiffened, and producing the required sections with the greatest efficiency of cost and weight.. Figure 5 summarizes the basic debate about deflanging versus fabricating. Each approach has advantages and drawbacks.



Stripped I-Beams

Advantages:
- Broad Experience
- Handles All Thicknesses
- Lower Capital Equipment Cost

Disadvantages:
- High Scrap Rate
- Limited Selection
- Distortion and Damage

Built-Up Tees

Advantages:
- Weight Savings
- Low Scrap Losses
- Wider Material Selection
- Minimum Handling
- High Speeds Available

Disadvantages:
- High Capital Cost
- Limited Experience

Figure 5. Comparison of Deflanged I-Beam vs. Fabricated Tee.

IV. CONCLUSIONS

- Fabricated tees offer a potential weight savings averaging 18% compared to hot-rolled I/T's.

The design analysis showed weight savings ranging from 9% to 25%, averaging 18% for the structures in the review. Using the conservative number, 9%, the potential reduction in weight for the target group of 1700 shapes amounts to more than 46 long tons. Structural integrity would not be compromised, since the weight reductions result from the more efficient section properties of the fabricated tee. One important consideration was that review of the design of the tees must proceed in concert with the review of the ship structures in which the tees are located, so that stability issues such as the affect on the vessel's center of gravity are not overlooked. It is also important to note that these weight reductions can be achieved using base metals of the same yield strength as the hot-rolled tees, not through substitution of higher strength material.[9] There is potential for greater weight savings through the use of hybrid designs which tailor material strength or other properties to design requirements. This degree of flexibility in design is not offered by the deflanging approach.

- Scrap material from the deflanging process averages 25% of material purchased.

Table I shows that 171 long tons of scrap are generated by the deflanging operation. This is more than 30% of purchased material. If purchase price of the I-beams was twenty-four cents per pound, this is a 1OSS of more than $90,000. Scrap per item varied from 20% to more than 30%. In contrast, scrap generated in the production of flange and web strip material for fabricated tees is on the order of 5% by weight.

- Processing costs for fabricating tees are generally lower than for stripping I-beams.

In general, welding methods and machinery can operate at higher speeds and duty cycles than traditional batch-type oxyfuel stripping gantries. In the fabricating operation, the production of web and flange strips may result in scrap on the order of 5% by weight of purchased material, hence there is a large saving in material cost when fabricating is compared to stripping. In addition, the fabricated tee can be designed to make better use of material, by custom sizing of web and flange to service requirements, resulting in the lowest possible design weight. Finally, using a "net shape" approach, in which flange and web pieces are cut to final size by NC from flat plate, further reduction in cost and handling may be achieved.

- Handling is a major cost driver for both fabricating and stripping operations.

Material handling within the shipyard to support deflanging of I-beams can account for more than 70% of total labor cost. Thus, increasing cutting process speed may offer only a slight drop in overall cost. In stripping, one piece is brought into the facility, and three pieces must be removed, only one of them a useful product. When tees are fabricated, however, two pieces are brought in and only one is removed. Most tee fabricating machinery is highly mechanized to reduce handling, and conveyor systems are a major part of the capital cost of such equipment.

- Continuous-process machines can offer significant cost reductions over batch-type methods.

Due to more efficient in-process handling, costs are lower even though four operators may be required (batch-type oxyfuel typically requires two). Large tee beam fabricating machines align parts accurately, and provide in-process straightening, resulting in minimal rework.

- The plasma-arc cutting process produces less distortion than the oxyfuel method.

Forty-foot beams stripped using plasma cutting showed camber to be reduced by 50%, compared to beams cut by the oxyfuel process.

- Water-spray reduces distortion in both oxyfuel and plasma cutting.

On the forty-foot test beams, a trickling stream of water from a small nozzle was directed onto the beams just after the cut. Camber was reduced by 50% compared to that shown on beams cut without water spray.

- Capital (acquisition) costs of equipment will affect the cost data of this analysis.

This project was concerned with a comparison of operating costs for deflanging I-beams and fabricating tees. Since there are many strategies for justifying and amortizing the cost of capital equipment, no attempt was made to factor in the acquisition costs of the equipment proposed for any given approach. On one hand, existing equipment may be modified, saving considerable expense. On the other, new buildings may have to be built to house a production facility. Thus, the capitalized cost of equipment may determine a final cost to produce a given range of tees, but all of the costs will be unique to the situation, and will include the specific details of production, such as the size of welds, variation in the work mix, total quantity of pieces, and other factors.

V. APPROACH

This following steps were taken:

- A design review compared the strengths of fabricated vs. hot-rolled I/T's,
- Existing and advanced technologies for deflanging I-beams were evaluated,
- Existing and advanced technologies for welding tees were evaluated,
- Relative economies of the methods were compared,
- Small-scale mock-ups evaluated promising technologies as to speed, distortion and quality, and
- Where possible, large scale mockups were used to evaluate the thermal distortion produced by a particular method.

To be at all manageable, this approach had to take into account some very practical limitations. First, this comparison had to have a target population of tee sections to use for analysis. To provide a well-understood group, the DDG-51 class hull was chosen. Currently in production at Bath Iron Works and the Ingalls Shipbuilding Division, this hull uses thirty different Tee shapes produced by stripping flanges from I-Beams which range from W6x9# to W20x55#. In all, more than eighty thousand feet of I-Beams weighing a total of nearly 690 tons are stripped to yield 519 tons of tee shapes. Scrap from the stripping activity weighs in excess of 171 tons and represents a significant loss (over $90,000 if purchased at recent prices). Table I shows this data.

Second, the comparative design was limited to evaluating a change from a hot-rolled tee to a fabricated tee with the same height and flange width dimensions as the tee it replaced. Thus, the design of the fabricated tee was constrained by keeping the envelope the same as that of the I/T shape. If the design of a vessel was based wholly on fabricated tees, there could conceivably be even greater reductions in weight of stiffening elements, but this is difficult to prove.

Third, any type of mock-up testing had to be done on available equipment, developed to meet existing needs and not capable of making long, parallel simultaneous cuts. Thus, laser and water-jet cuts had to be done sequentially in two passes, on relatively short pieces of material. While cut-edge quality and speed could be compared, it was impossible to realistically estimate the kind of distortion which might be experienced with these technologies for comparison to that produced by the traditional dual-torch OFC method. Fortunately, Plasma-Arc Cutting equipment was loaned to Bath Iron Works for this project and installed on the production bar stripping gantry, so that beams could be deflanged.

Finally, an economic analysis of production costs and rates must necessarily be limited in the number of potential scenarios treated, and rely on some often "heroic assumptions." Review of manufacturer's data can provide much good information, but the final cost will depend on the implementation of the method and the degree of utilization (duty cycle) actually maintained by production personnel. This project has attempted to evaluate a number of these factors to determine an optimum approach to the manufacturing of stiffeners. Knowing that local conditions may require different solutions to the same problem, a further goal has been to provide enough information to allow the reader to evaluate different situations.

Table I I-Beams Stripped to Make Tees for DDG-51

Depth in.	I wgt #/ft	T wgt #/ft	Scrap #/ft	Scrap % Loss	Lgth each, ft.	Qty	Total Feet	Total I Wgt, #	Total T wgt, #	Scrap Total #
8	10	7.48	2.52	25.2%	40	2	80	800	598.4	201.6
10	15	11.64	3.36	22.4%	40	17	680	10,200	7,915.2	2,284.8
8	18	12.92	5.08	28.2%	20	25	500	9,000	6,460	2,540
6	9	6.43	2.57	28.6%	49	195	9,555	85,995	61,438.7	24,556.4
8	10	7.48	2.52	25.2%	49	319	15,631	156,310	116,919.9	39,390.1
8	13	9.9	3.1	23.8%	49	67	3,283	42,679	32,501.7	10,177.3
10	12	9.49	2.51	20.9%	49	154	7,546	90,552	71,611.5	18,940.5
10	17	12.89	4.11	24.2%	40	25	1,000	17,000	12,890	4,110
10	19	14.24	4.76	25.1%	49	15	735	13,965	10,466.4	3,498.6
12	14	11.27	2.73	19.5%	49	216	10,584	148,176	119,281.7	28,894.3
12	16	12.83	3.17	19.8%	49	139	6,811	108,976	87,385.1	21,590.9
12	19	14.81	4.19	22.1%	49	10	490	9,310	7,256.9	2,053.1
12	22	16.78	5.22	23.7%	49	46	2,254	49,588	37,822.1	11,765.9
12	26	18.24	7.76	29.8%	49	47	2,303	59,878	42,006.7	17,871.3
12	30	21	9	30.0%	49	24	1,176	35,280	24,696	10,584
12	50	33.25	16.75	33.5%	49	8	392	19,600	13,034	6,566
14	22	16.85	5.15	23.4%	49	56	2,744	60,368	46,236.4	14,131.6
14	26	19.54	6.46	24.8%	49	64	3,136	81,536	61,277.4	20,258.6
14	34	24.21	9.79	28.8%	49	21	1,029	34,986	24,912.1	10,073.9
14	43	29.11	13.89	32.3%	49	24	1,176	50,568	34,233.4	16,334.6
14	26	20.13	5.87	22.6%	49	28	1,372	35,672	27,618.4	8,053.6
16	31	23.53	7.47	24.1%	49	25	1,225	37,975	28,824.3	9,150.8
16	36	26.44	9.56	26.6%	49	10	490	17,640	12,955.6	4,684.4
16	40	28.82	11.18	28.0%	49	9	441	17,640	12,709.6	4,930.4
16	45	32.47	12.53	27.8%	49	2	98	4,410	3,182.1	1,227.9
16	50	36.03	13.97	27.9%	49	14	686	34,300	24,716.6	9,583.4
18	35	27.12	7.88	22.5%	49	35	1,715	60,025	46,510.8	13,514.2
18	40	30.27	9.73	24.3%	49	42	2,058	82,320	62,295.7	20,024.3
18	50	36.48	13.52	27.0%	49	46	2,254	112,700	82,225.9	30,474.1
18	60	43.51	16.49	27.5%	49	13	637	38,220	27,715.9	10,504.1
20	55	44.18	10.82	19.7%	20	18	360	19,800	15,904.8	3,895.2
				Total Pieces:		1,716				
					Total Feet:		82,441			
						Total Wgt (#):		1,545,469	1,163,603.1	381,865.9
						Wgt. (LTons):		690	519	170.5
									% Scrap Loss:	25%

Processing and Production Concepts

Two distinct scenarios have been used for processing T-sections in the fabricating industry. Stripping methods have generally used a batch-type approach, with multiple bars being deflanged simultaneously by a gantry moving over the parts, and fabricated tees have traditionally been produced by a continuous method, with a single part being passed through a fixed welding head. Given these traditions, however, variations within the schemes are conceivable, and have been used, especially when one looks at equipment for welding stiffeners to panels. Stiffener welding gantries, made to weld several stiffeners to plates simultaneously; can be used to manufacture batches of tee shapes just as well.

The advantage of batch processing is greatest when the cost per process installation is relatively low compared to the cost of the gantry or station. The traditional oxyfuel deflanging gantry is a good example. Torch carriages can be added to a gantry for a relatively low cost. If four or more I-beams can be processed at once, many of the cost elements per cycle are divided by four. In contrast, higher-speed methods like laser cutting may cost 100 times as much per cutting head as oxyfuel equipment, and can reasonably be expected to be more cost-effective only in a continuous-process mode, gaining their advantage from higher processing speed. Batch-type machines usually require only slightly more floor space than the longest piece to be processed, whereas continuous processing lines require a length equal to more than two times the longest piece.

Continuous processing has been used for many installations where high speeds are achieved, and the cost of the process is relatively high. Usually, continuous-mode production is not considered to be very flexible, in that machinery tends to be designed to do large volumes of particular sizes, either very heavy sections as in bridge beams or very small, as in High Frequency Resistance Welding (HFRW) equipment, and the concept of making many different sizes in any kind of “just-in-time” approach is not intuitive. Nonetheless, if the entire volume of stiffening elements is considered, it may be economically feasible to justify more than one machine. Further, the operating range of equipment may be expanded by minor modifications in design.

Beyond the relative merits of batch and continuous production, there are other aspects of the production of stiffeners which should be considered. Figure 5 shows three conceptual approaches to providing stiffening elements for shipbuilding. Method A is the deflanging, or I-to-T stripping, in which I-beams are received from steel mills and the flanges are burned off, and stock lengths of tees are inventoried for later cutting into structural details. Scrap, easily 25% of the new material is generated at the deflanging stage and must be removed, rework may be required, and significant handling is incurred. Material must be supplied and inventoried both upstream and downstream of the stripping operation, well in advance of production requirements. When schedules calls for specific tee elements, the I/T's are drawn from stock, laid out, and cut to the desired length and configuration. Scrap is generated at this stage as well.

Method B shows the fabrication of stock-length tee sections from plate or strip material. Steel bars or strip are provided either by cutting plate or purchasing hot-rolled flats. Scrap may or may not be generated depending on the approach. Flange and web are aligned and fit, typically with substantial manual effort, and joined, usually by semi-automatic welding methods. For light sections, welds are usually much larger than needed. Significant distortion may occur during welding, requiring rework. Little scrap is generated, but handling may be extensive. Again, material is inventoried both upstream and downstream in the production flow to assure that there

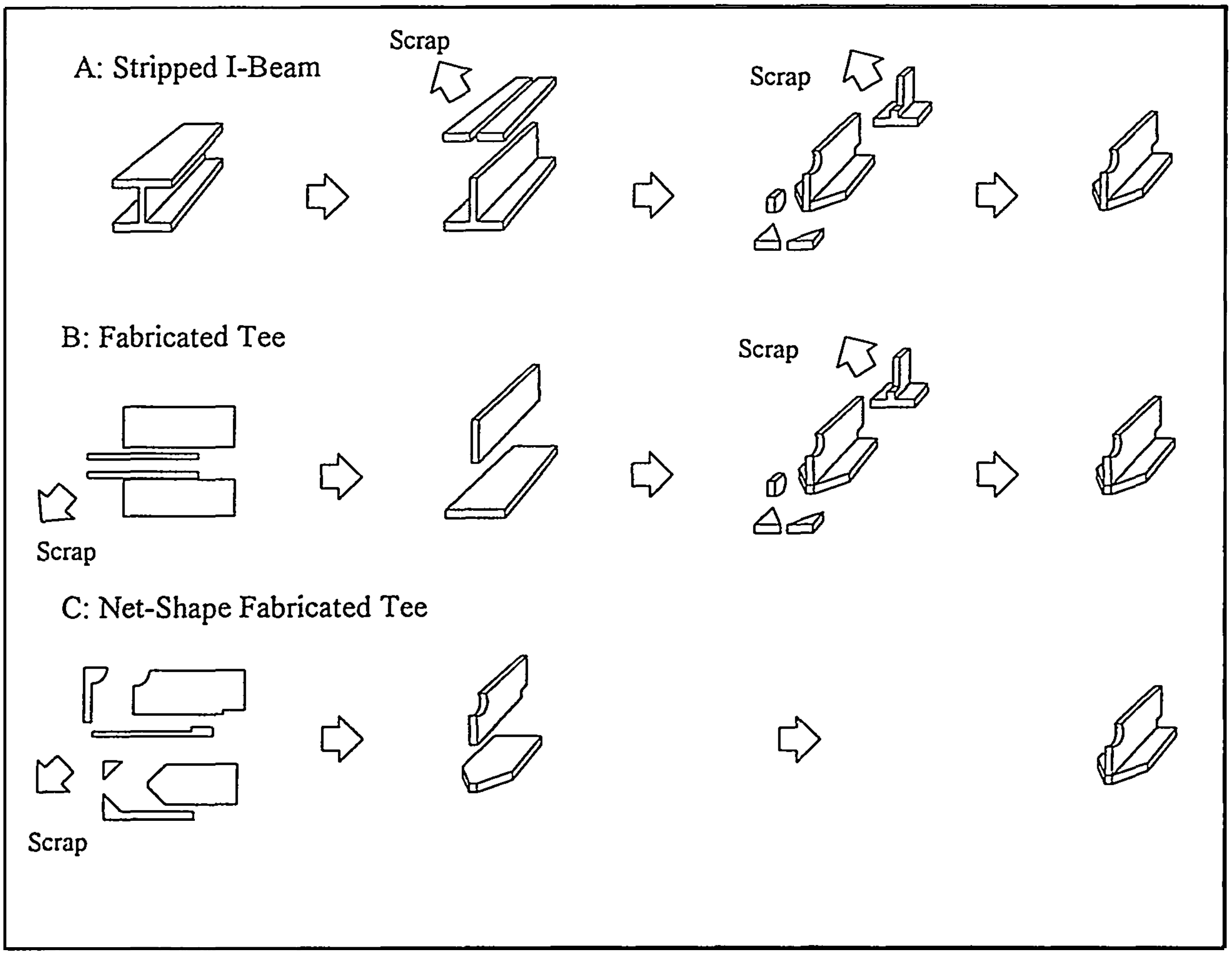


Figure 6. Concepts of Tee Stiffener Production

are tees available for cutting into detail pieces when schedules require. The final step is the same as done in A.

Tees could be made of standard "Universal Mill" bar stock, and indeed, at least one shape-rolling company does this, providing large sections which fit into gaps in the catalog of split I-beams. This in effect establishes another catalog, and forces design tradeoffs between required strength and final weight. Thickness and width of such plates may be sufficiently varied to give enough selection so that weight compromises are less severe than those forced by the availability of I-beams for stripping to tees. In this case the fabricated tee produces no scrap until the final detail cuts are made.

A and B are fairly well known and used, the differences being only of scale. The traditional approach is that Tees are produced by method A if there is an I shape with reasonably close sectional properties, and method B is used everywhere else. Because the final use is not known at the time of production of the welded Tee, the weld must always be 100% efficient, even though, in the many of applications, the weld which will join the tee to the deck or shell need only be 60-70% efficient in places.

For production of stiffening elements on a shipset scale, method C is a different approach entirely. All web and flange sub-pieces would be cut using NC plate cutters to final shape from flat plate, and joined into the "net-shape" stiffener. Scrap is generated only in the plate cutting phase, and handling and inventories could be significantly reduced. Through efficient nesting of material, scrap could be minimized. The main concern is that tracking of pieces is critical to success. The ideal reduction of inventory would have the flange and web piece being cut at nearly the same time, and immediately being routed to an automatic welding station. The concept of efficient nesting, however, would require that some inventory of web and flange parts be maintained as the processing of different thickness plates dictated. This implies a thorough method of storage and retrieval on a scale not used before. With the increase in the use of computerized job tracking and bar-coding on the shop floor, the question becomes more one of size and execution than one of absolute possibility or impossibility.

"Net shape" production of tee elements also requires the use of automatic welding equipment to be successful. Manual fitting and tacking must be eliminated, and welding must be reliably done at the highest practical speeds. Through computer control of all job factors, including the part identity of the actual piece, the correct size and shape of weld can be made more nearly according to design requirements. New methods such as laser welding offer potential for high speed welding with fill penetration with minimum fillet reinforcement.

The obvious further demand on equipment flexibility is that in addition to different sizes, many different lengths must be produced, and the traditional concepts of tee fabrication all involve the production of standardized long pieces only.

At first it would appear that method C is not used at all, but that is not really the case. It shows up in the fabrication of web frames: very large and fairly complex to be sure, but tee sections nonetheless. The use of method C to produce smaller or shorter tees in any significant volume has not been reported, but the concept is intriguing. An aspect of stiffener production which is seldom considered is that the shipyard must buy and inventory a suficient quantity of I-beams to meet the production rate of a bar stripping facility. This facility then makes a "second inventory" of shapes which are issued out and processed later into usefud ship parts. The cost of the extra material needed, and the lead time necessary to support these schedules are difficult to clearly state. A "net shape" approach does away with all of this, but the implementation is no simple matter.

Shapes other than tees have been fabricated, including angles and channels. One foreign supplier currently makes oversized bulbed flats by welding the bulb portion to a piece of flat stock. Angle-sections have been considered difficult in the past because of the corner-joint configuration, and were often made as offset tees. Laser welding can overcome this limitation, and some angles have been produced with fill-penetration welds. The analysis of costs to produce net shape structural elements on a large scale is beyond the scope of this project. It would be an excellent follow-up study.

VI. DESIGN REVIEW

The design review examined the strength and weight characteristics of welded tees versus stripped I-beams as applied to the DDG-51 design specifications. The purpose of this analysis is to determine the potential weight reduction which can be achieved if fabricated Tee shapes are substituted for stripped I-Beams. It is plausible that plates and sheets can be obtained with a greater freedom of choice of material thickness, and therefore, weight, than hot-rolled structural shapes. Since "the next larger" shape than that required by design is selected from the catalog, the final form of the fabricated shape should be more nearly equal to the design requirement, resulting in weight savings with no sacrifice in performance.

Therefore, this phase investigated these questions:

- Can a given population of various Tee shapes for a specific vessel be manufactured from plate with a net savings in weight?
- What are the savings possible, and will a significant loss of strength result from design tradeoffs?
- Are there any negative effects which will show the substitution of fabricated shapes to be impracticable or inadvisable?
- For the stability and performance goals of a given vessel, will the savings in weight of tee sections have any negative effects?

Since the loading requirements and performance issues of the DDG-51 vessel are well-known, the specifications and fabrication documents were used to recreate the design scenario for selected portions of the structure. In contrast with the traditional approach of design with stripped beams, these areas were evaluated for actual section requirements. Then a trial design of a fabricated tee-shape was made, using available thicknesses of plate material. A significant constraint used was that the fabricated shape must conform to the same envelope as the stripped shape it would replace. While restricting the freedom of design for the purpose of weight reduction, this allows the consideration of changing an existing design with minimum impact on outfitting, such as cable runs, pipe hangers and ventilation.

This analysis yielded these conclusions:

- Fabricated Tee sections would have adequate strength, and would reduce the overall cross-sectional area (and therefore, weight) of stiffeners by 18%, compared to stripped I-beams of identical depth and width.
- Ž For the population of shapes investigated, the maximum area reduction shown was 24%, and the minimum was 9%. Based on the more conservative figure of 9%, substitution of fabricated shapes for stripped shapes could save 46 tons.
- Reducing the weight of Tees "across the board" would have an effect on the ship’s vertical center of gravity, and therefore, stability. (This can be compensated by changes in shell plating thickness, or other methods.)
- Fabricated shapes offer potential for producing even lighter hybrid designs, e.g., a high-yield flange welded to a lower-strength web, etc.

This evaluation was carried out by Brian Miller of BIW's Structural Engineering department. Mr. Miller's analysis is contained in Appendix A, "Engineering Evaluation." To provide a diversity of expression and stimulate thought on the part of the reader, there has been no attempt to editorially change any of the analysis or opinions expressed. In fact, the only comment that the author would add to Mr. Miller's analysis, is in regards to the effect of stiffener weight reduction on the ship's vertical center of gravity (VCG). Truly, the mere reduction of stiffener weight across the board should not be made without considering effects on stability. However, if stiffener weight is reduced, the loss of stiffener weight below the VCG could easily be compensated by using thicker plating in the hull below the VCG. This would have the beneficial effect of increasing resistance to damage due to impact or corrosion. Furthermore, tank bulkheads and other structures may be evaluated, and made thicker as needed in these areas. This kind of thought process will be of greatest benefit in a new ship design, if the traditional approach of using the stripped I-beam is questioned at the outset.

Other somewhat traditional issues which need to be addressed when comparing the fabricated tee to the deflanged hot-rolled beam are weld design and fatigue performance issues. The hot-rolled beam offers a relatively homogeneous area and a generous radius at the flange-to-web transition, all of which are beneficial for strength and fatigue performance considerations. Welds, on the other hand, may or may not be fill penetration, and profiles may vary, influenced by several procedural parameters. Often, the connection of the web to the flange does not always need to be 100% efficient (the weld may not need to equal the base metal strength) for a stiffener to perform properly, given the typical loading of many structures.[10] What is important to remember is that welded connections can be designed and produced to meet all service conditions. This is underscored by the fact that in every case where hot-rolled shapes are not available, fabricated stiffeners are used, and perform well. [11]

Finally, the fabricated tee offers significant opportunity for flexibility and creativity in the design process. Webs may be supplied with lightening holes designed for specific properties, for instance. These are far more efficiently cut from flat plate on NC/Plasma equipment at the time the web strips are produced. One company involved with High Frequency Resistance Welding demonstrated production of light weight tee and I-shapes with remarkably improved buckling resistance by using a corrugated web. [12]

Further reductions in weight may be possible if a new vessel is designed "from the keel up" using fabricated shapes. Freed from the constraint of having to duplicate hot-rolled shape outside dimensions, more efficient shapes can be designed. Web thicknesses below traditional minimum values may be possible as well.

VII. METHODS REVIEW

The methods review evaluated a number of cutting and welding technologies, emerging as well as traditional, which could be applied to the manufacturing of tee sections for stiffening ship panels. The purpose of this phase is to identify the more promising techniques for further analysis of cost, quality, and productivity; for small-scale mockup testing, and, where appropriate, large scale mockup testing.

While it is plausible that machinery for producing welded tees should be at least as productive as that currently used for stripping, one must also consider that more modern methods of deflanging may also exist, and that these methods should be reviewed alongside the potential welding techniques, and the method with the lowest overall cost chosen for production.

This phase attempted to determine:

- If a given process can produce the target population of various tee shapes,
- What production rates are possible,
- What the acquisition and consumable costs for the equipment are, and

Ž The dimensional and surface quality the process yields.

Relevant literature and experiences of those in other industries were sought to determine the potential of various methods for producing tee sections by either deflanging or fabricating. New technologies were considered, especially those which promised greater efficiencies in production. Since there are so many variables in the configuration of a system capable of dealing with shipset quantities of tee sections, a study of this nature must necessarily be qualitative rather than quantitative.

Once a number of likely methods were identified, those most likely to produce shipset quantities of tee sections were scheduled for small scale mockup trials, and evaluated to establish what modifications might be necessary for making the method into an efficient production tool.

Cutting and Welding Methods Applicable to Stiffener Production

The following methods were selected for review, based on demonstrated success in similar production situations, or, in some cases, on the potential for high speed or high accuracy. In the discussions which follow, costs are estimated based on the process equipment at its simplest level, without extensive material handling equipment. In general, the addition of infeed and out feed conveyors and stock and scrap handling equipment could add as much as $500,000 to the costs listed.

Cutting Methods

Cutting methods identified in this review are summarized in Table II. A brief description of each process follows.

Table II. Stripping Methods					
Process	**Speed**	**Cost**	**Consumables**	**Flexibility**	**Quality**
OFC	1-2 fpm	Low	Gas, Tips	Med	Fair/Good
PAC	2-7 fpm	Med	Gas, Noz., Elctd., Tips, Pwr	High	Good/Exc
LBC	3-16 fpm	High	Gas, Pwr	Med/High	Good/Exc
Cold Saw	0.5 fpm	High	Blades, Fluid	High	Exc
AWJC	0.1-0.5 fpm	High	Water, Grit, Nozzles	High	Exc
Arc Saw	5-30 fpm	Highest	Power, Blades	High	Unknown

Oxyfuel cutting (OFC)

The traditional method for producing tees from I-shapes, OFC'S strength lies in its wide base of experience, inherent flexibility, and low equipment cost. Its main disadvantages are low travel speeds, high heat inputs, and relatively large kerf, with the propensity to damage webs when the flame is too close.

Oxyfuel equipment is inexpensive and fairly easy to maintain. When an installation for producing tees has been designed, the cost of adding multiple torch carriages is reasonably low ($2-3 K), so that significant parallel processing can be used to reduce the labor costs. OFC equipment can cut any thickness of steel in use in stiffeners today, needing only to change inexpensive cutting tips. This is in contrast with laser and plasma cutting equipment, for which thickness capacity is related to machine power output levels, and the cost of doubling the capacity may increase the capital cost for equipment by a factor often or more.

Thermally induced distortion is arguably the highest in OFC, since the process has the highest heat input. Distortion may be reduced by optimization of parameters, use of water sprays, and pre-cambering, but OFC still generates significant quantity of material which requires post-straightening. Other quality problems arise when a cut is made too close to the web, leaving a scarfed or gouged area which must be repaired by welding and grinding.

Fully adaptive control of the OFC process, i.e. dynamic changes to pressures and orifices, has never been fully explored. In light of the more amenable electronics and easily measurable process parameters available with laser and plasma cutting, these methods have been used where wide control of the process is desired. Furthermore, the OFC's low speeds provide a disadvantage for increasing the cost and complexity of equipment. As a result, OFC equipment used in stripping operations suffers from a lack of fine control, and this can lead to a certain amount of rework as a result. Figure 7 shows how OFC cutting speeds compare to PAC and LBC.

Plasma Arc Cutting (PAC)

PAC provides significant improvements in speed and reduction of heat input. The process is well understood, equipment is rugged, reliable, and electronically controllable. Prior to the introduction of oxygen-capable plasma systems, PAC was not a serious contender for use in

I-beam deflanging: the range of tolerance of parameters to produce relatively slag-free cutting was too narrow, even though cutting speeds could be generally faster. This is even more important in bar stripping than in plate cutting, since the actual thicknesses are quite varied, and the thickness in the area to be cut is not constant across its width. Any movement of torches or misalignment of web to flange causes a change in cut thickness due to the radius transition from flange to web.

The use of oxygen as a plasma gas has resulted in a broader window of travel speeds to produce cuts with minimal slag adhesion. Inverter-type plasma cutting power supplies offer greater energy efficiency, produce narrower ketf, and are more tolerant of variations in stand-off distance.

Unquestionably, plasma cutting offers the same boost to cutting speed for I-beam processing that it has given to NC plate cutting. However, plasma equipment suffers from the fact that speed improvements are significant only in the thinner materials, and drop sharply as thickness increases. For the current range of thicknesses of tee sections in this study, plasma still enjoys a speed advantage over OFC, and as long as the work mix favors the thinner sections, overall processing times can be significantly reduced. This can be seen in Figure 7.

Plasma technology is more expensive than OFC, easily ten times as much, but is typically less than one-tenth the cost of lasers, water jets, and cold saws. Inverter-type plasma equipment costs approximately $10K for a unit which will cut all the thicknesses in the target group of tees. To strip one bar, two units would be needed.

Electrical power, cutting gases, and torch parts such as electrodes and tips are the major consumables required for plasma cutting. Consumable parts life is markedly shorter with oxygen plasma than that experienced by the older nitrogen plasma systems, but the improvements in cut quality, speed and the generally wider range of parameters at which slag-free cuts can be made have moved oxygen plasma into dominance in this field.

PAC is reasonably flexible, although, for the purpose of this study, the ability to cut materials other than steel is a moot point. The only drawback is that equipment capable of processing the greatest thickness must be purchased, even though the thicker items may be a small percentage of the total work mix. Comparatively, since the travel speeds for OFC are slow even on thin material, the drop-off with increasing thickness is less noticeable.

As seen in NC plate cutting, PAC can produce acceptable edge quality. The traditional problem of "inherent bevel" has been dramatically reduced by the introduction of oxygen plasma gas as well as the use of inverter technology. Inherent bevel is less of a problem for Tee-bar production, since the cut progresses in a single-axis straight line, so that torches can be inclined to compensate for any bevel which might be experienced. The higher travel speeds possible should logically produce less distortion than that seen with OFC due to reduction of heat input. The use of water sprays and pre-cambering could further reduce heat-induced distortion.

Laser Beam Cutting (LBC)[13,14,15,16]

Laser Cutting is gaining in acceptance in the manufacture of light-gauge materials, and power levels have been increasing while cost per kilowatt has been decreasing. Unquestionably, the power density achievable is the highest of the available cutting processes, and this fact alone suggests that thermally-induced distortion should be the lowest with lasers compared to any of the other thermal processes.

C02 lasers in power levels up to 25 kW are available, although the highest power units are seldom used for cutting. Multiple-rod Neodymium-doped Yttrium Aluminum Garnet ("YAG") lasers have been produced in versions up to 2.4 kW, and programs are underway to produce a solid-slab YAG device of 6 kW capacity. Within the distinction of C02 and YAG, there are several competing technologies, such as RF-pulsed, fast -flow, diode-pumped, slab, etc. Each may offer specific benefits in speed or quality within its power range. YAG lasers offer the unique ability to use fiber-optics for beam delivery, allowing the laser to be located in a favorable area, while the flexible fiber can be deployed in a typical shop atmosphere. This could be an enormous benefit for shipyards, as the special attention to beam delivery required for C02 devices is avoided, and a greater choice of configurations for tee-bar processing equipment is afforded.

While laser technology is promising, the amount of demonstrated success in heavy-section cutting remains limited, and cutting speeds tend to drop off with increasing thickness for a device of any given power level. Considering the high population of relatively light sections used in surface combatants, this may not prove a significant limitation, but for large commercial vessels with generally thicker sections of ordinary strength steels, this could be a handicap.

Certainly, the potential for very high cutting speeds exists, although, there is not a large base of industrial experience in thick-section cutting to support this claim. In addition to factors such as beam quality, the design of nozzles and beam focusing optics is critical. Development in this area has been demand-driven, and therefore limited to thinner materials. Nevertheless, speeds of up to 4 fpm were demonstrated in the mock-up test phase of this project, using equipment clearly designed for thinner sections.

Carbon-dioxide lasers at power levels of 1-3 kW cost in the neighborhood of $250,000 while the equipment of 10 kW and higher can cost several million dollars. YAG equipment of 2.4 kW capacity is similarly priced to C02 equipment of equal power. Note that the cost is dependent on several factors, and due to technology growth, may change significantly in the near future.

Since the current technology of higher powered laser devices produces equipment which is 10-14% electrically efficient, power is a major cost element. Obviously, gases, and to a lesser extent, nozzles and lenses are consumable items.

As with plasma cutting, laser systems are power-dependent: for any given power level, as thicknesses increase, cutting speeds are reduced, drastically, in the case of the lower-powered (1 kW) devices. The implications of this are enormous, in that today’s high-power devices are limited to C02 technology, and can cost several million dollars, as mentioned above. While high quality cuts have been demonstrated in materials 3/4-inch and thicker, travel speeds are reduced, and at some point, thermal attributes of the base metal begin to dominate the chemical reactions in cutting, and some of the advantages of high power density are mitigated. Considering Figure 7, it is apparent that LBC shows the steepest drop-off of speed with increasing thickness, when compared to OFC and PAC.

For thinner sections, laser cutting yields near-machined quality surfaces. Translating this experience to thick carbon steel with surface rust and mill scale is a significant challenge. Logically, some of the high quality seen in the current experience base of thin materials may carry over into the thicker plating typical of I-beams, however, this remains to be proved.

Cold Sawing[8,17]

Cold sawing, a machining method, is a relatively low-temperature process, and has been increasingly used for cutting steel plates and structural shapes. Cold circular saws have provided a high quality, cost-effective alternative to band saws and oxyfuel equipment. The advantages of cold sawing for I/T production are superior edge quality, the ability to cut arbitrarily close to the web of the beam, and the potential for reduced distortion offered by an essentially non-thermal process. A significant consideration, however, is the residue of cutting fluid, which if not removed, could affect the weld quality.

Cold saws can work at speeds up to 4 fpm, based on experience with flat plate cutting. These systems often are rated on volume of material removed, or the area of the cut face. Some systems have quoted rates, such as 12-24 cubic inches removed per minute, so that travel speed would depend on blade thickness. Since the saws are highly precise, there are implications to the tolerances in ASTM A-6, which allow significant flange tilt, off-center flanges, and other dimensional inaccuracy. Equipment may be designed to overcome this, but it will add to the expense.

Cold saw set-ups cost in the neighborhood of $250-500K, depending on the amount of material handling equipment. In this case, they are almost always configured with some conveying equipment, and the demands of material handling specific to tees may alter this cost range greatly.

Blades are the major consumables for cold sawing, although resharpening can be done. Cutting fluid is next in importance, especially considering the impact of increasingly stringent environmental regulations. Chips produced in the process are recyclable, but may require special handling due to the presence of the fluids.

Cold Sawing can handle the entire range of thicknesses required, will produce a true machined-suface quality, and should result in low distortion by virtue of low heat input and use of cutting fluids.

Abrasive Water Jet Cutting (AWJC)[18]

AWJC has been used to cut many "problem" materials, from very hard ceramics and metals to foam products, with great accuracy. For I-beam stripping, the low heat input would produce little distortion, but slow production rates and high installation and maintenance costs make it economically unfeasible.

AWJC can cut at speeds up to 6 inches per minute on soft materials or light gauges of metals. Cutting rates drop to below 1 inch per minute on 1-inch thick steel. Equipment, including pumps, intensifiers, distribution systems and manipulators can cost up to 500K. Since pressures up to 50,000 psi are used, wear is significant, and maintenance costs are high.

Water and abrasive grit are the major expendable. Although garnet grit itself is not a particularly hazardous material, it forms a sludge in the water tables. This is non-recyclable because of the metal content, and incurs a fairly high disposal cost.

Excellent cut surfaces are produced by AWJC, and distortion to parts is insignificant. The method is highly flexible, in that it can cut all materials, but application is limited due to low travel speeds.

Arc Sawing[19]

This recently-developed technology uses a spinning metal disc, or blade, which transfers current from its edge to the workpiece. Extremely high currents, several thousand amperes, are used, and high cutting speeds are possible. The equipment is capable of running completely submerged in water, and all current installations of this equipment are being used to cut up decommissioned nuclear reactor vessels. This obviously limits the amount of experimentation which might be carried out at existing installations. Very little work has been done to establish the applicability of this equipment in other environments, however, the manufacturer reported a test in which an 8-inch diameter high nickel alloy (625) round bar was transversely cut, to compare with the use of abrasive cut-off saws. The abrasive saw took 10 minutes to make the cut, while the arc saw severed the bar in 8 seconds. Quality of the cut face was not as good as that produced by the abrasive method, but no development work was done to determine if edge quality could be improved.

Arc sawing equipment costs approximately $750K, not counting any material conveying systems. Handling equipment would have to be capable of coping with the high electrical currents involved. Enormous amounts of electrical power (6,000 Amperes) are used, and blade consumption could be a significant expense, since blades cost $250 each and each pair of blades would need to be replaced after 500 to 1,000 feet of cut, or approximately twenty bars.

Cutting speeds of 30 feet per minute are possible on 3/16-inch material, dropping down to 5 fpm on 1-inch thick steel. Cutting action might be affected by the geometry of tee sections. This is a reasonable assumption because of the high currents and the unsymmetrical cut face which I-beam presents to the blade. In some cases, arc blow is induced in welding by such transitions. The edge quality which could be produced on an I/T is difficult to estimate, since this equipment has been only used for cuts in large, flat plates..

Welding Methods

Welding processes reviewed are summarized in Table III. More traditional welding methods such Gas Metal Arc Welding (GMAW), Flux-cored Arc Welding (FCAW) and Submerged Arc Welding (SAW) have a well-established range of typical procedures. Some work has been done in the arena of pulsed GMAW for high speed applications, and the field of Laser Beam Welding (LBW) is relatively untried in this form of manufacturing: i.e. heavy sections, high production volume.

Table III. Welding Methods

Process	Speed	Cost	Consumables	Flexibility	Quality
GMAW/FCAW	2-6 fpm	Med	Wire, Gas, Pwr	High	Exc
GMAW-P	2-10 fpm	Med/High	Wire, Gas, Pwr	High	Exc
SAW	2-7 fpm	Med/High	Wire, Flux, Pwr	High	Exc
LBW	3-12 fpm	High	Pwr, Wire	Med/High	Exc
HFRW	200 fpm	High	Pwr, Coolant	Low	Exc

Gas Metal Arc and Flux Cored Arc Welding (GMAW/FCAW)[20,29]

Both of these processes have been used widely for production of fillet welds with mechanized equipment. Flexibility and quality are outstanding, and equipment is relatively inexpensive, reliable, and readily available. Travel speeds will vary with the size of the weld required (see Figure 7), and will largely depend on the deposition rate of the electrode and welding parameters chosen. A new variation is the use of “Metal-Cored” electrodes, which have been seen to offer higher productivity with excellent arc stability and weld cosmetics. Major consumables are welding filler metal, which generally costs on the order of $1.00/1b, and shielding gas. These processes are reasonably well-understood, thus discussion will be purposely limited.

Pulsed Gas Metal Arc Welding (GMAW-P)[21,22,23]

A very small amount of work has been reported in which extremely high speeds (120 to 180 in/min.) have been achieved using GMAW in conjunction with very specialized pulsed power supplies. In general, weld sizes at these speeds have been small, so it is not known if this approach will provide the flexibility to perform large-scale welding of ship-sized structural elements, especially in the commercial arena. Costs of the consumables are the same as above, but the equipment is not widely available, and may be more expensive than traditional GMAW power sources. Continued development of this process may result in equipment capable of welding at speeds comparable to those offered by laser welding at a significantly lower price.

Submerged Arc Welding (SAW)[2’]

SAW has produced more fabricated tee shapes than any other welding method. Again, the process is well understood, and although equipment is generally more expensive than GMAW/FCAW setups, it is still reasonably priced ($5-10K per arc). The process offers outstanding flexibility and generally faster travel speeds than "open-arc" methods, even for large welds, through the use of multiple wires. Other advantages of SAW are the low level of smoke produced and the lack of significant arc radiation, although these are not major factors where highly mechanized equipment is concerned. SAWS higher travel speeds will usually reduce distortion, although straightening by some means will still be required. This is often done in-process by an in-line heating torch applying balancing heat to the opposite edge of the web, and acceptably straight pieces are produced. Figure 7 shows estimated travel speeds for welding fillets in the size range needed for tthe group of tees in this analysis.

Laser Beam Welding (LBW)[24.2S]

LBW has grown in use in the last decade, producing high-quality, high speed welds with low distortion on a wide variety of materials. The fundamental disadvantage of the process is its high equipment cost, but prices may drop as LBW becomes more widely used. In fabricating tees, one significant fact associated with laser welding, as opposed to cutting, is that penetration by one beam through the entire thickness is not needed. If the design calls for full penetration, two opposing beams need only penetrate slightly more than 50% of joint thickness. Two lower powered lasers may cost much less than one high-powered device, but ultimate power levels will still be governed by the deepest penetration required. LBW produces excellent quality autogenous welds in steels, and if reinforcing fillets are needed, the process works well with filler metal additions.

Laser welding at speeds over 150 in/min. is possible for thinner sections (<3/16 in) included in this analysis. Travel speeds drop off for thicker materials (see Figure 7), especially with lower powered devices, but power level is not always the best criterion for evaluating a laser system. Factors such as beam quality, brightness, and spot size can have bearing on a particular application.

Laser systems cost from the hundreds of thousands of dollars for 1-3 kW devices to several millions for 14-25 kW sources. Since most lasers are only 10-15% electrically efficient, large amounts of electrical input power are necessary, but less than that required for cutting, since less penetration is needed. Plasma-suppression gas (helium) is usually necessary. Although it seems intuitive that some filler metal is needed to provide an acceptable weld surface contour for good fatigue performance, some published work has shown that fill-penetration autogenous laser welds with small fillet profiles have provided excellent fatigue performance, comparable to much larger fillet welds made by other processes.[32,33]

The only shortcoming of present laser systems is the high cost of devices with power levels sufficient for fast processing of the thicker parts seen in this review. This has some impact on consideration of lasers for commercial ship work.

LBW has been shown to provide high quality welds in a variety of demanding situations. For full penetration welds with small reinforcing fillets, it is expected that laser welding will yield the lowest overall distortion in as-welded parts, due to its very high energy density and high travel speeds.

High Frequency Resistance Welding (HFRW)[6,7,31]

This process has produced large amounts of lightweight I-beams for truck trailers and mobile homes. High current at high frequency is passed between web and flange connections, heating the junction quickly to forging temperature. Pressure rollers force the parts together for full-penetration welds. Machinery is huge (hundreds of feet long), expensive, and suited to large lot production, but runs at extremely high speeds (up to 200 fpm). The method is generally used on lighter materials (3/8” and less), and works best with coiled strip, handled by unloaders and on-the-fly coil splicing stations. The method could be considered if large quantities of light weight sections are needed, but might not be able to handle the thickness of commercial ship stiffeners. HFRW was recently used to provide HSLA tee sections of approximately 6#/foot for later-flight CG-47 class vessels. Approximately 40,000 feet of these shapes were used per ship. As a footnote to the necessity for large, repetitive orders to make HFRW equipment commercially successful, the company which produced these HSLA sections was later forced to close due to low demand.

Comparison of Processing Speeds

To provide a basis for comparison in the cost analysis portion of this project, certain methods were selected, and more detailed estimation of processing speeds was made, based on the thickness to be cut, or the weld size to be made. Cutting processes selected were OFC, PAC, and LBC. Welding processes were GMAW, SAW, and LBW.

Cut thickness for I/T'S was estimated at the sum of the flange thickness plus one-half the radius of the web to flange transition. This resulted in a thickness range of 0.3- 1.0 inch. Cutting speeds were estimated by consulting manufacturer's literature and other sources. [13,14,15,24] LBC speeds were based on a 5 kW enhanced (RF) pulsed C02 device using oxygen as an assist gas.

Welding speeds for GMAW and SAW were taken from handbook data and filler metal manufacturers' literature for fillet welds. Fillet sizes were based on standardized tables for producing fillets sized to achieve 100% efficiency, based on the thickness of the web and flange. For the materials here, fillets from 1/8-5/16 in. were needed. LBW speeds were based on fill penetration welds with minimum fillet reinforcement, using a 10 kW C02 laser operating at sufficient power to achieve approximately 50+% penetration from each side.[24] Filler wire addtions were assumed to provide minimum fillet reinforcement.

These estimates are summarized below in Figure 6. Full details of material thickness, weld size and travel speed are contained in Appendix B.

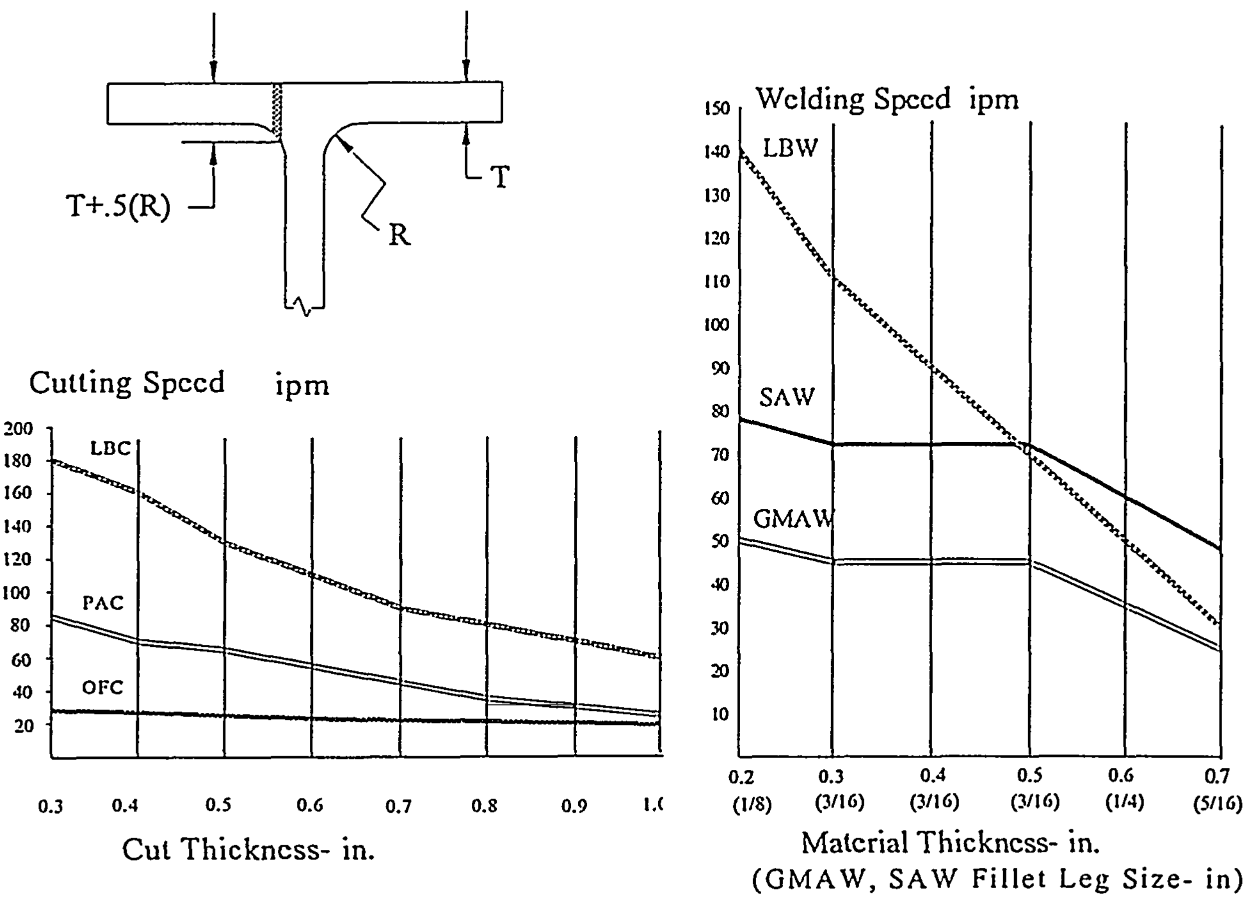


Figure 7. Estimated Cutting and Welding Speeds

VIII. Cost Analysis

Conducted fourteen years ago by NSRP, the Semi-Automatic Beam Line (SABL) Feasibility Study[27] provides a good base line of the cost to provide stripped I-beams for tee stiffeners. The SABL study compared the productivity of "standard methods," measured at a shipyard, to that of a proposed highly mechanized facility for the processing of structural shapes. That project looked at the overall processing of all structural shapes including such things as end cuts and web fabrication, and beam deflanging was treated as one of several operations. The study did not go into specific process details, or break down general categories into specific process elements. However, it showed that handling was a major cost-driver, and that significant savings could be realized in the this task. Since the SABL study did not propose to change the basic technology (oxyfuel cutting) for deflanging I-beams, there was little need for functional detail. Furthermore, the SABL study did not look beyond the boundaries of the processing facility: the issue of material transport into and out of storage was treated as a constant, and handling for I-beam stripping referred to movement of material within the facility to and from the stripping process.

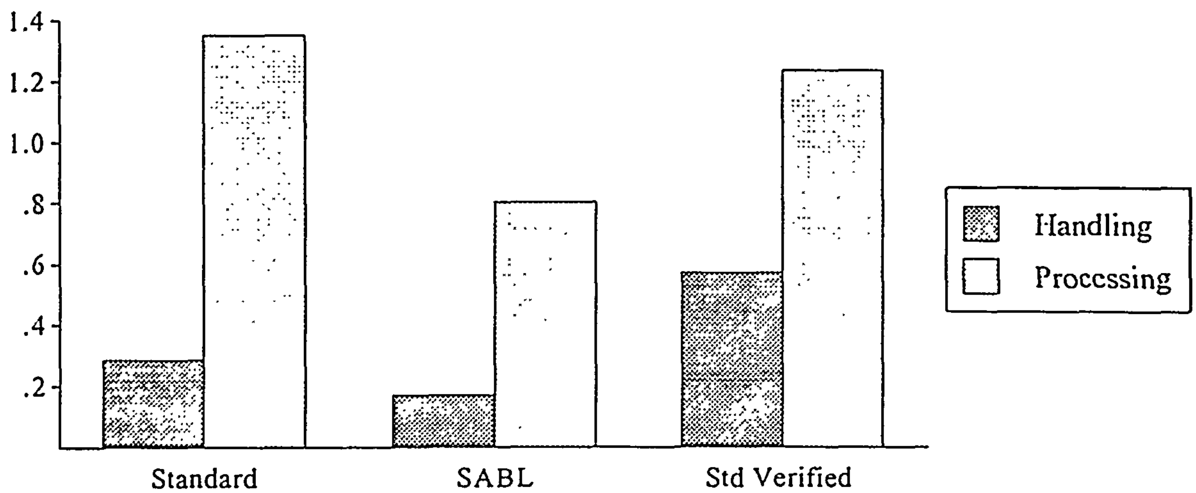


Figure 8. Verification of SABL Study Data, labor hours per part.

Notes:

1) "Processing" includes those handling functions which are directly related to cutting
2) "Handling" in verified data includes moving material to and from outside inventory
3) Overall product quality and rework was not mentioned in the SABL study.

Using the SABL study data as a base-line, This project analyzed the current stripping functions in greater detail. A time study was made of beam stripping functions, both to verify that the cost of the SABL study's "standard method" was similar to current practice (since the basic method, OFC was the same), and to evaluate areas where process improvements might have the greatest benefits. Figure 8 shows a primary comparison, in which "standard verified" refers to data collected in this time study. To provide a parity with the SABL breakdown, some detailed process elements have been lumped together under "processing." In the SABL study, the standard methods required approximately 1.3 labor hours (Lhr) to process each part. Handling, as mentioned above, for the Standard and the SABL comparison referred to the time spent on moving material within the facility, to and from the burning process. This was documented at 0.286 Lhrs for the Standard method. Since there may differences in handling methodology between the location where the SABL study was performed and the location of the current project, it is not expected that identified handling costs will be identical. What is significant is that processing times are reasonably equal for both analyses.

Since the movement of material into and out of inventory storage is a cost element, the "verified standard" data reports "handling" as the movement of material to and from storage areas into and out of the processing facility, and is approximately 0.57 Lhrs per part.

The SABL study claimed that costs could be cut substantially, and the SABL data in Figure 8 show a reduction of about 40% for both processing (from 1.35 down to 0.8 Lhrs/part) and handling (from 0.286 down to 0.171). The facility improvements offered by the SABL concept were entirely material handling devices such as conveyors and mechanized alignment and locking fixtures. No process changes, such as substituting PAC for OFC, were suggested, nor was it proposed that OFC parameters be changed. Rework was not addressed as a cost element which would benefit from the new equipment.

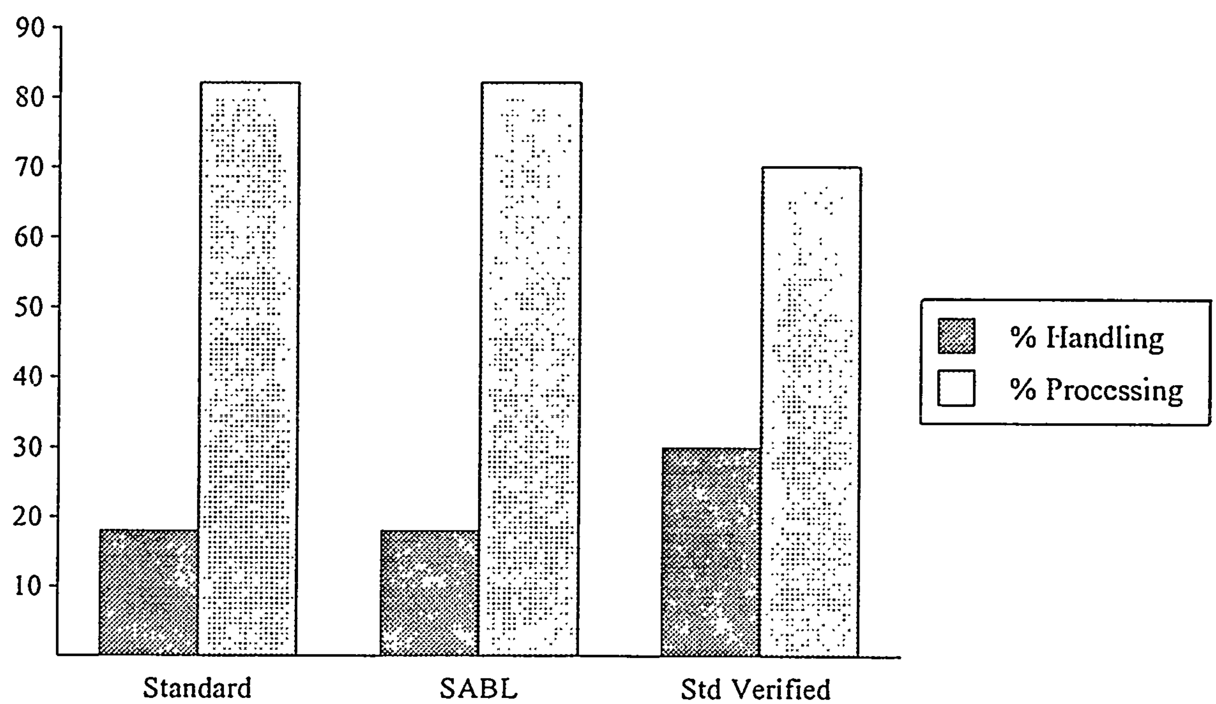


Figure 9. Relative Percentage of Cost Elements of Standard, Verified, and SABL

Since the “processing” improvements offered by the SABL system do not result from changing operating parameters of the process, they must arise from the more efficient handling of material within the process. Figure 9 shows that the ratio of handling costs to cutting costs did not change. Thus, the “processing” cost element in the SABL study must include some time-related handling functions, such as setting up and scrap removal. With the SABL study, although handling has been reduced by 40%, it remains 18% of the total cost of stripping. The reduction of 41% in processing cost has to result from faster set-up, since process parameters have not changed.

The verified data treats the issue of material handling as specifically the movement of material into and out of inventory storage, and in-process handling was lumped together for comparison purposes. Since any comparison of the relative cost of alternatives must include the entire range of functions, and continuous-processing machinery will have different handling costs than batch-mode equipment, a more detailed functional breakdown is needed. This was not necessary for the SABL study, where the processing technology was not an issue for analysis. The processing methodology (oxyfuel cutting) is the same for both the Standard data and the Verified data, and they compare well to each other. It is fairly safe to assume that these baseline costs are typical for the industry, and that any differences would lie in the relative efficiency of application of material handling to service the burning process. As mentioned above, these comparisons have not addressed rework.

The next step is to break down the verified data into greater detail and include information about the amount of rework. In Figure 10, process time has been broken into three component parts, two of which involve handling, and rework has been added. Rework is driven by an internal standard, and in this case, the goal is to produce finished parts with only half the camber allowed by ASTM A-6 for any given shape. If the A-6 guidelines were followed exactly, 50-foot beams would be allowed 1.25 inches of camber, and only 10% of the parts would need straightening. At a tolerance of one-half of the ASTM allowed value or 0.625 inch, nearly 50% of parts produced by oxyfuel cutting typically will need some rework. Thus, the decision as to the output tolerance of the processing system can change this percentage greatly.

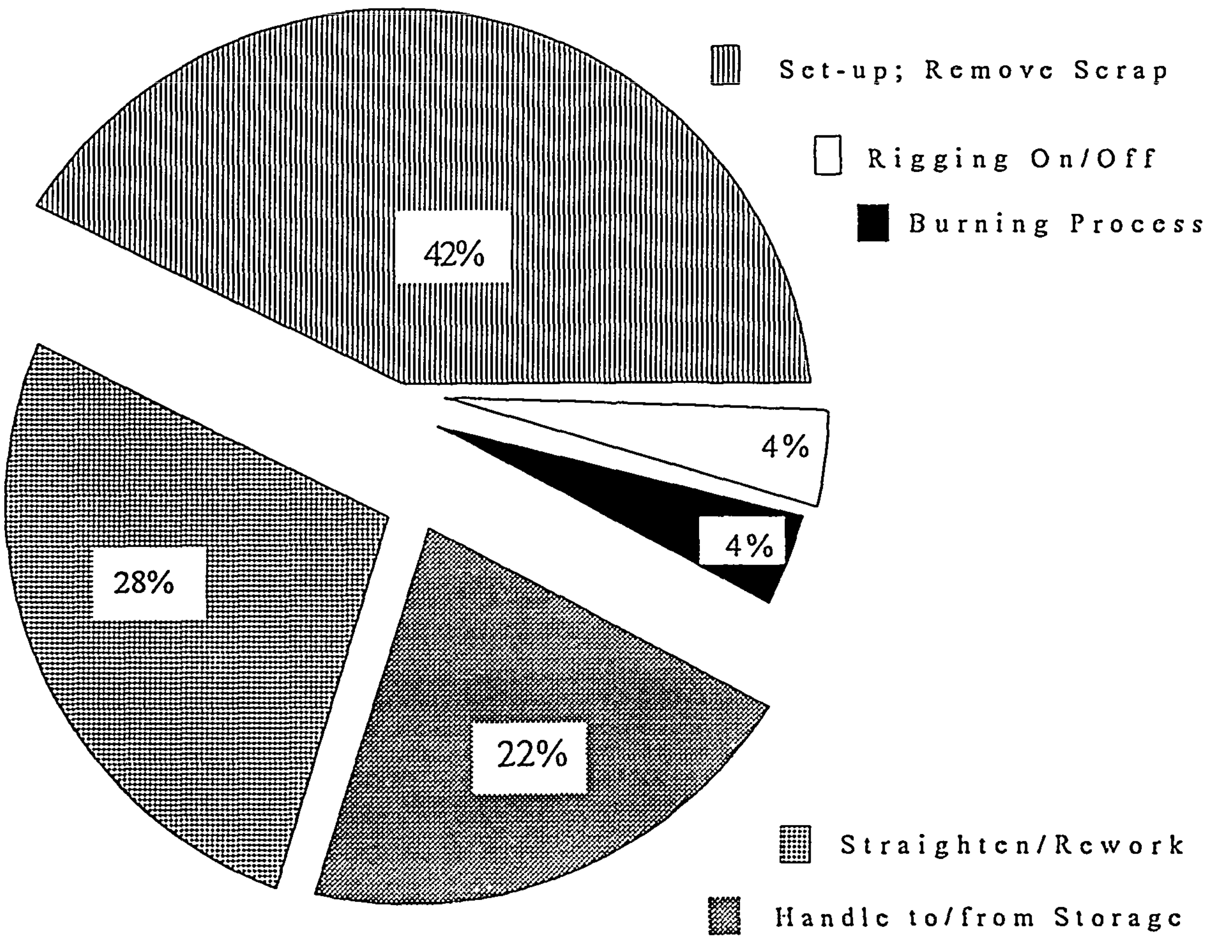


Figure 10. Percentage of functions involved in stripping process

Notes:
1) "Set-up" is time to align four beams prior to burning, and to remove scrap flanges. (1.13 Lhrs/bar)
2) Rigging stripped tees out of the fixtures and loading new I-beams. (0.10 Lhrs/bar)
3) Actual burning process time, multiplied by number of operators. (0.10 Lhrs/bar)
4) Straightening is done if finished tees exceed 50% camber allowed by ASTM A-6. (avg. 0.75 Lhrs/bar)
5) Handling to/from storage refers only to moving material to and from the stripping area. (0.57 Lhrs/bar)

Projected Costs

To provide a comparison of the relative costs of fabricating and stripping methods, seven methods have been evaluated. Four cutting methods are the standard oxyfuel cutting (Std-OFC) method, re-equipping OFC batch-processing gantries with plasma-arc cutting (Batch-PAC) capability, continuous-processing plasma-arc cutting (Contin-PAC), and continuous-processing laser cutting (Contin-LBC). Three welding methods have been reviewed, all of them considered as continuous-processing tee fabricating machines: submerged arc welding (Contin-SAW), typical gas metal arc welding (Contin-GMAW), and laser welding (Contin-LBW). Manufacturers of this equipment and other sources were consulted to provide reasonable estimates of travel speeds and processing times. In most cases, for other than laser and plasma processes, these values are well-documented and easily verified by virtue of many successful applications. Laser cutting and welding have not been used in applications of this thickness range, and to some extent plasma cutting has not been used for the particular geometry, so that estimates of expected rates have been made based on available literature.

A comparison of relative functions for a continuous SAW tee fabricating machine is presented in Figure 11. In this treatment, the handling times for moving material to and from inventory are included at the same level as those measured for the verified OFC batch method. Loading and unloading times are based on data presented by a manufacturer of tee-making equipment, and welding times were verified by both experience and several manufacturers' data. Significantly, preparation of stock material from plate is a major cost element, at 36% of the total. With handling at 32%, it is evident that a major savings can be achieved if tee production can be done on the "just-in-time" and "net-shape" basis referred to earlier, in which the finished product goes directly to production in its final form.

For the projected cost comparison, a number of assumptions had to be made:

- Capital cost of the equipment was not considered.
- Final costs were the summation of production costs, including handling times.
- Cutting speeds were based on thickness of the flanges plus half the radius of transition from web to flange (see also Figure 7).
- Welding speeds were based on that necessary to produce the required fillet weld size, to provide 100% efficiency for the thicknesses to be joined; full penetration welds were not assumed except for the case of laser welding, which also assumed small-sized reinforcing fillets.
- Based on experience with continuous-process welding machinery, rework was not factored into the welding scenarios.
- Cutting methods had rework added in at the experienced rate of the verified data for standard OFC, and half that for the other (faster) cutting methods.
- A standard rate of 4 labor hours per plate (handling and burning) was used to calculate processing time to produce strips for tees from plates. The total of flange and web widths plus kerf was used to estimate the number of plates required, and the scrap produced.

Once this data was entered, several production cost scenarios were generated. Matrices of detail data appear in Appendix B. Since labor cost, material cost and machine utilization are all major elements in overall cost, each was varied while the other two were held constant, to evaluate the effects of changes on production costs. Labor rate was factored in steps from \$15/hr to \$40/hr. Material costs were figured from \$0.18/lb to \$0.30/lb. In assessing the affect of varying duty cycle, for batch processes, the experienced standard data was used throughout, which is why the lines for Std-OFC and Batch-PAC are constant. Since any machine is profitable only when it is used, however, duty cycles from 50% to 95% were calculated for the continuous-process implementations. Considering that a tee fabricating machine usually only requires a 15-second delay between finishing one section and starting the next, the 95% maximum was somewhat conservative.[28]

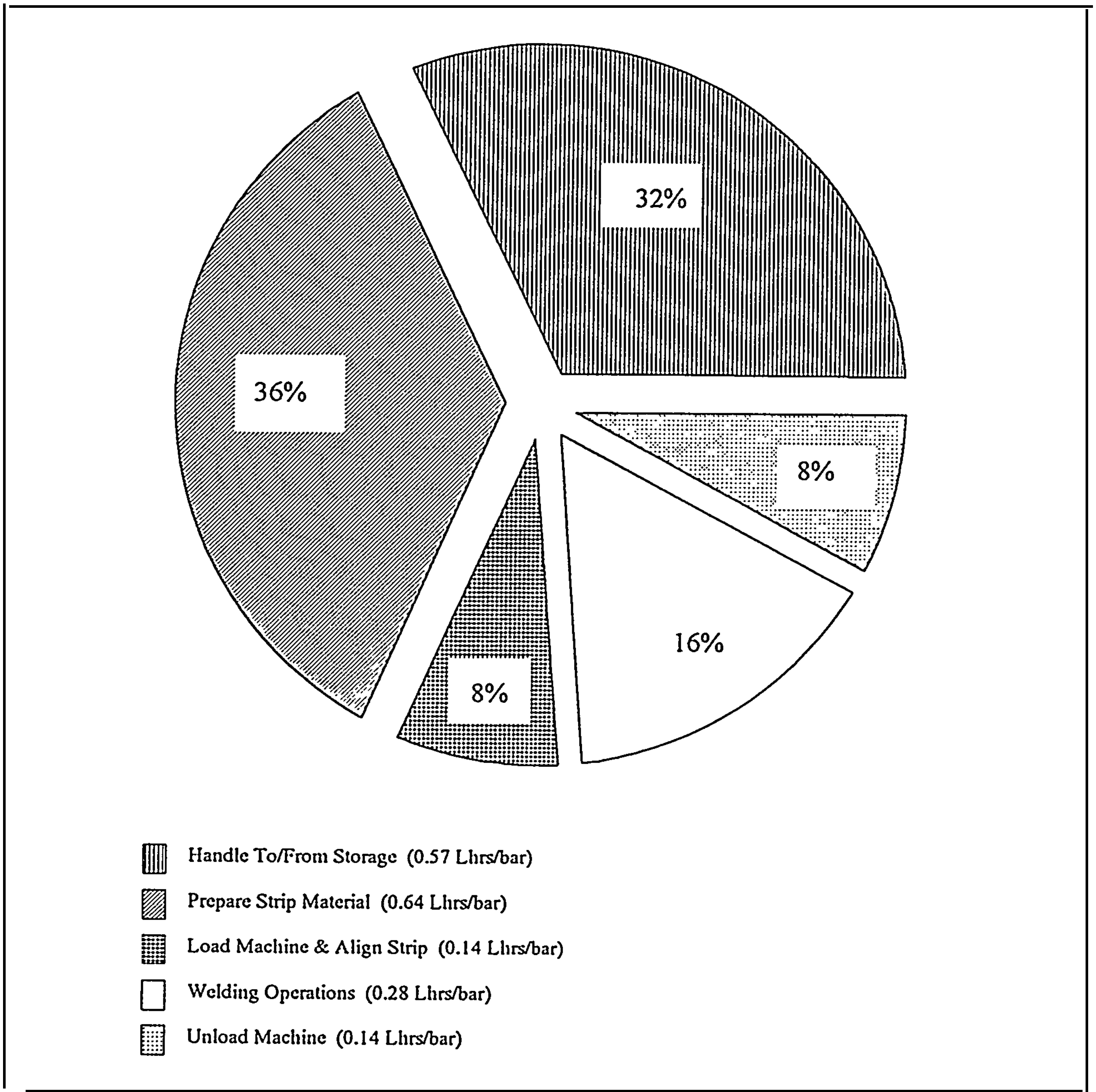


Figure 11. Percentage of Functions in Continuous Process SAW for Tee Fabrication

As a further attempt to consider these scenarios on a reasonably equal footing, the travel speeds of oxyfuel cutting were based on manufacturer's charts, nearly two feet per minute in most cases, and were substantially higher than those used in current production. As mentioned elsewhere, since the burning time in the current process amounts to only 4% of the total labor per piece, there is no substantial reduction in overall costs from the calculated increase in speed.

This analysis yields these conclusions:

- In virtually every case, the overall cost to fabricate was lower than the cost to strip, frequently by as much as 30%.
- The main reason for the large difference is that 25% of purchased material is lost as scrap in the cutting operations.
- If processing scrap is not considered, fabricating methods are still lower in cost.
- Laser processes show the lowest cost in each review, but there is little practical experience to back up the performance estimates.
- Of the traditional processes, submerged arc welding shows the best overall cost performance in each of the scenarios, thus it is not surprising that this process has the greatest industry experience in the fabrication of tee sections.

Figure 12 shows a comparison of relative costs for batch OFC, continuous LBC, continuous SAW, and continuous LBW. What is significant is that the total cost for fabricated tees is only slightly higher than the material cost of the I-beams for either of the deflanging methods. Further, even at the estimated high cutting speeds of LBC, the cost advantage offered does not reduce overall cost below the cost of welding. Note also that LBW and SAW are close in production cost. If the capital cost of equipment were factored into the analysis, the high cost of laser devices would tend to rule out their acquisition.

This data is presented in greater detail in Tables IV, V, and VI, and Figures 13, 14, and 15 provide the information in graphical form.

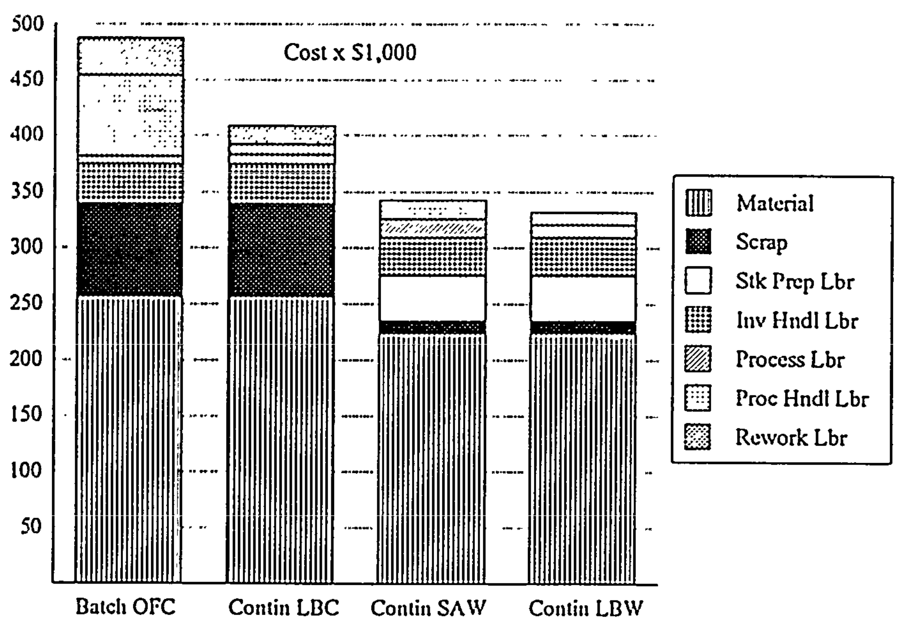


Figure 12. Processing Cost of Batch OFC vs. Continuous LBC, SAW, & LBW

Table IV. Processing Cost (x$1000) vs. Labor Rate (@ $.22/lb and 95% Duty Cycle)						
	Labor Rates, $/hr					
	15	20	25	30	35	40
Std OFC	404	425	446	467	488	510
Batch PAC	394	411	429	447	464	482
Contin PAC	377	390	402	415	427	440
Contin LBC	369	379	389	399	409	418
Contin SAW	280	296	311	326	342	357
Contin GMAW	289	308	325	344	362	381
Contin LBW	276	289	303	317	331	344

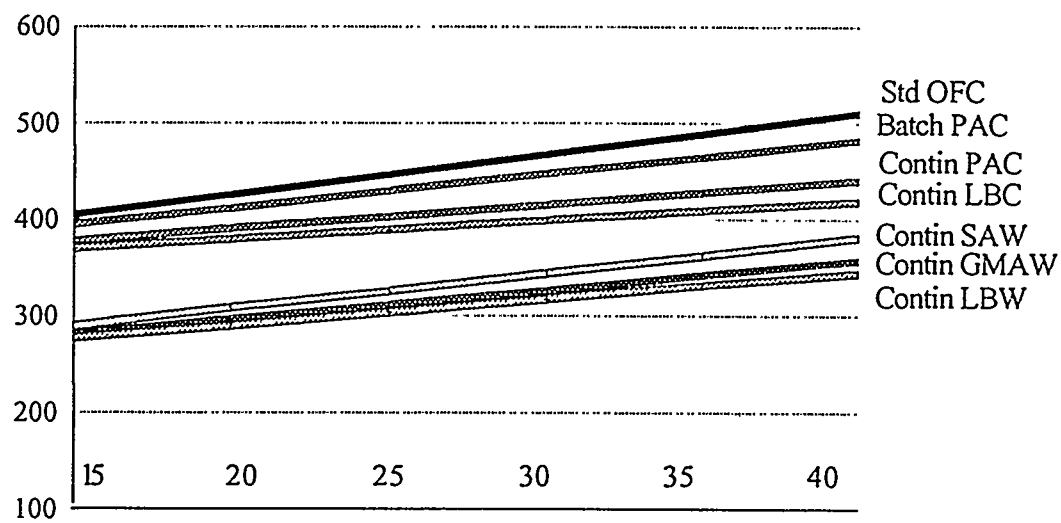


Figure 13. Processing Cost (x$1000) vs. Labor Rate ($/hr)

Table V. Processing Cost (x$1000) vs. Steel Cost (@ $35/hr and 95% Duty Cycle)							
	Steel Cost, $/lb						
	0.18	0.2	0.22	0.24	0.26	0.28	0.3
Std OFC	427	457	488	519	550	581	612
Batch PAC	403	434	464	496	527	558	589
Contin PAC	365	396	427	458	484	520	551
Contin LBC	347	378	409	440	470	501	532
Contin SAW	299	320	342	363	384	406	427
Contin GMAW	320	341	362	384	405	426	448
Contin LBW	288	309	331	352	373	395	416

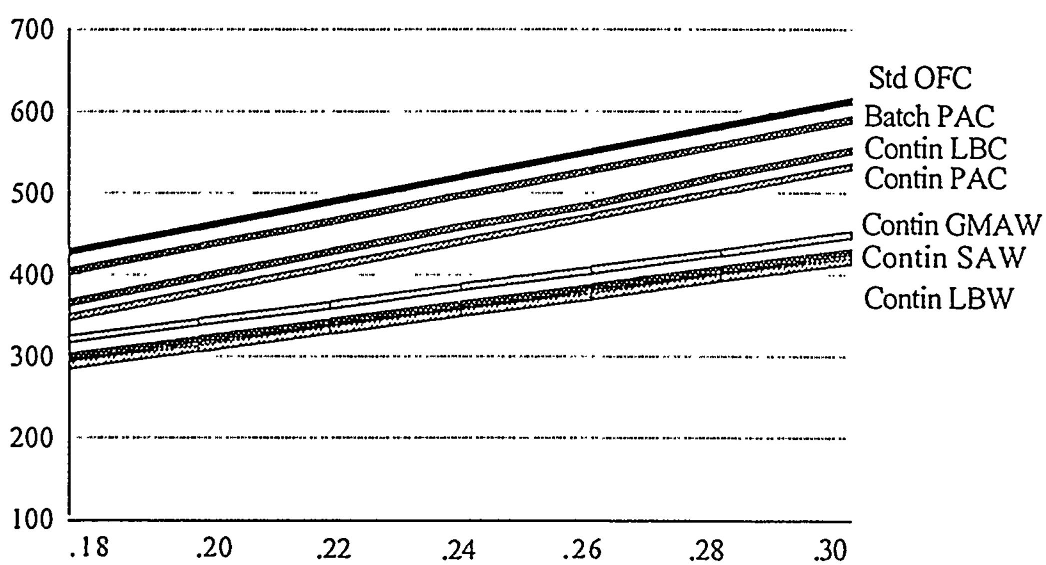


Figure 14. Processing Cost (x$1 000) vs. Steel Price ($/lb.)

Table VI. Processing Cost (x$1000) vs. Machine Duty Cycle (@ $.22/lb and $35/hr)							
	Machine Duty Cycle						
	0.5	0.6	0.75	0.8	0.85	0.9	0.95
Std OFC	488	488	488	488	488	488	488
Batch PAC	465	465	465	465	465	465	465
Contin PAC	460	448	437	434	431	429	427
Contin LBC	424	419	413	412	411	410	409
Contin SAW	372	361	350	348	346	344	342
Contin GMAW	411	394	377	373	368	365	362
Contin LBW	351	344	337	335	333	332	331

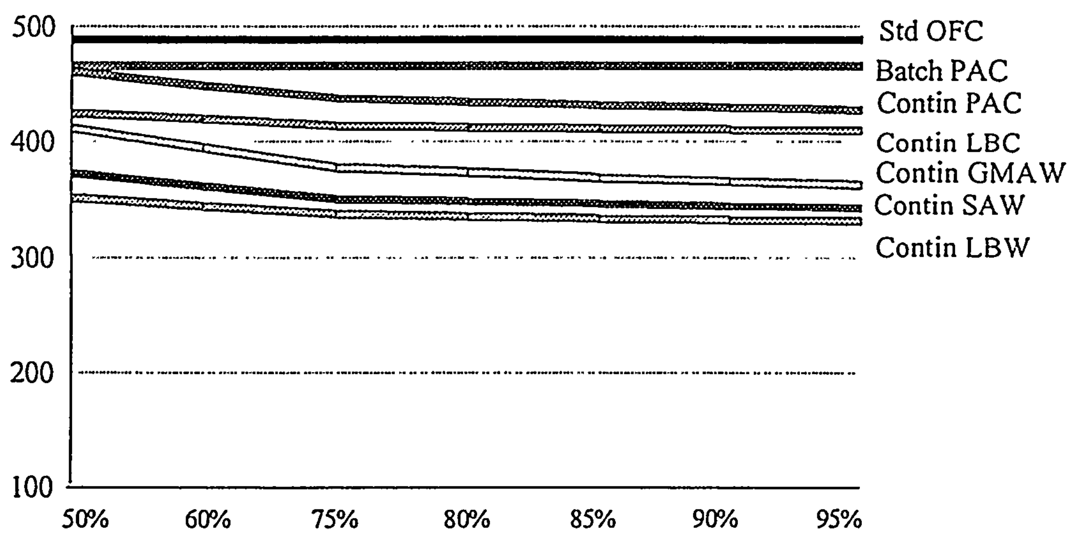


Figure 15. Processing Cost(x$1000) vs % Duty Cycle

IX. MOCK-UP TESTS

Where appropriate equipment was available, mock-up tests were conducted to provide insights into each of the methods under consideration in this review. Processing speed and cut quality were evaluated, and, as much as possible, distortion induced by the process was measured. In many cases, existing equipment was simply not configured to do a close approximation of a stripping cut, or to make tee-section welds. In most of these cases, only one cutting head or welding head was available, so the stripping or welding operation was done in two sequential operations. This provided some degree of judgment about how the process might perform if adapted to the task of producing tee shapes, although the effect of two simultaneous cuts or welds could not be fully proved. Small-scale mockups were used to establish parameters for a given speed and quality, and large scale mockups were used to evaluate distortion. Naturally, the ability to do large parts was limited. Abrasive water jet cutting was done to evaluate if there were residual stresses contained in the flanges, which would become unbalanced and cause distortion even in a non-thermal process.

To provide a standard section for cutting tests, 6x20# wide-flange beams, in the mid-range of weight and thickness of the target group, were used. These were cut into sections of the maximum length possible for processing at the given facility. In general, test pieces were only two feet long, but a few eight-foot pieces were cut. Laser tests were made using lasers of as many different types as possible.

Since the traditional welding processes are well understood, only one welding test was performed, using C02 laser welding. The 6x20# shape was approximated by using 3/8x6 inch flat bars for both web and flange.

The mock-up tests are documented in greater detail in Appendix C, which includes appropriate photographs of the test pieces.

The following small-scale mock-up cutting tests were performed:

- Laser cutting of two-foot sections at Applied Research Laboratory, PennState University, using 2.4kW YAG and 1.5 kW C02 lasers.
- Laser cutting of eight-foot sections at ARL using the 14 kW C02 laser.
- Laser cutting of two-foot sections using the 3 kW GE Fanuc C02 laser at Edison Welding Institute.
- Laser cutting of two-foot sections using a 3 kW YAG laser at Hobart Laser Products.
- Abrasive water jet cutting of an eight-foot section at Laser Applications Inc.
- Oxyfuel cutting of eight-foot sections at Bath Iron Works

The following large-scale mock-up cutting tests were performed:

- Oxyfuel cutting of forty-foot sections at Bath Iron Works
- Plasma-arc cutting of forty-foot sections at Bath Iron Works

The following large scale welding test was performed:

- Laser welding of twenty-foot sections using the 25 kW C02 laser at Stardyne, Inc.

Included for information are photographs of a machine temporarily used at Bath Iron Works for submerged arc welding on forty-nine foot long HSLA-80 tee shapes.

Summary of Mock-up Tests

- For most laser and plasma cuts, edge quality was nearly as good as that attained with oxyfuel processes, and for most cases, higher travel speeds were noted than those used for traditional burning.
- In general, the processes tested performed at lower speeds than originally estimated. Typically, this was due to the radius at the flange to web transition.
- Abrasive water jet cutting produced no measurable distortion in an eight-foot beam, but eight-foot sections were too short to provide significant distortion with any process.
- Plasma cutting of forty-foot sections resulted in approximately half as much distortion as that produced by oxyfuel cutting.
- Water sprayed on the parts being cut will reduce distortion by nearly 50%.
- Autogenous laser welds in twenty-foot parts produced little distortion, but when filler metal was added to provide fillet reinforcement, distortion increased.

Distortion measurements taken are summarized below. It is unfortunate that more data could not be generated in this program, especially for long sections cut by other processes. The use of eight-foot sections did not provide enough length to gain much insight into potential distortion which might be produced by laser cutting. Indeed, the oxyfuel result for eight foot parts is contradictory, but the numbers are so small that it is difficult to draw a conclusion.

Water spray remains one of the simplest and most useful methods for reducing distortion. A light spray of water, or a trickling stream from a small nozzle will have a dramatic influence on final camber of a deflanged beam. As the table below shows, the use of the water spray gave a better than 50% reduction in camber for both the plasma and oxyfuel processes.

Table VII. Distortion Measurements

Process	Measured Camber (inches)				
	8' Dry	8' Water	40' Dry	40' Water	20' Welded
AWJC, single cut		0			
LBC (14 kW C02), single cut	1/16				
OFC, single cuts	1/32	1/16			
OFC, double cuts	1/8	1/8	4-21/32	2-3/16	
PAC, double cuts			2-3/4	1-3/16	
LBW (25 kW C02), autogenous					5/32
LBW (25 kW C02), w/filler added					9/16

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TEE BEAM MANUFACTURING ANALYSIS

FOR

WEIGHT REDUCTION AND PRODUCIBILITY

NSRP PROJECT #N7-91-4

APPENDIX A

TO

FINAL REPORT

ENGINEERING EVALUATION

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700 Washington Street
Bath, Maine 04530

October 31, 1994

Overview

The design review has examined the strength and weight characteristics of welded tees versus stripped I-beams as applied to the DDG-51 design specifications, and yielded the following **conclusions:**

- Fabricated Tee sections would have adequate strength, and would reduce the overall cross-sectional area (and therefore, weight) of stiffeners by 18%, compared to stripped I-beams of identical depth and width.

- For the population of shapes investigated, the maximum area reduction shown was 24%, and the minimum was 9%. Based on the more conservative figure of 9%, substitution of fabricated shapes for stripped shapes could save 46 long tons.

- Reducing the weight of Tees “across the board” would have an effect on the ship’s vertical center of gravity, and therefore, stability. This can be compensated by changes in shell plating thickness, or other methods.

- Further reductions in weight are possible if a new vessel is designed “from the keel up” using fabricated shapes. Freed from the constraint of having to duplicate hot-rolled shape outside dimensions, more efficient shapes can be designed. Web thicknesses below traditional minimum values may be possible as well.

- Fabricated shapes offer potential for producing even lighter hybrid designs, e.g., a high-yield flange welded to a lower-strength web, etc.

Background

Most ship designs have required tee shapes for stiffening panels (decks, shells, and bulkheads). Typical mill practice of splitting I-beams down the center of the web (e.g., a 12-inch deep I yields two 6-inch tees) does not provide a shape with proper section properties for ship panel stiffening. This is in large measure due to the optimization of I-shapes for the building construction industry, by far the largest consumer of these shapes. A convenient workaround to this problem has been the traditional approach of removing one pair of flanges, so that the 12-inch I becomes a 12-inch tee. This yields a section with adequate properties for ship panel stiffening, and provides a readily available source of material of convenient length for processing, with minimal labor input on the part of the shipyards.

I-beam stripping is typically done using the Oxy-Fuel Cutting (OFC) process, with some sort of mechanized gantry or other device to move the torches over the beams. While this equipment is simple and reliable, the OFC process tends to cause warpage from its high heat input and may cause damage to webs due to errors in torch tracking. Frequently, the torches are offset from the web to avoid this damage; this practice leads to added weight, and makes welding of the tee shape to the panel more difficult, especially when mechanized panel line equipment is used. A further downside to the deflanging approach is that 25% of the material purchased is turned into scrap.

Since the design process yields values for section properties (the "design shape") which are not necessarily exactly those of a section available from steel producers, the "next larger" shape is chosen from the catalog. Flange and web thicknesses and widths of available shapes may also be disproportionate to those of the design shapes. The net result is greater weight and cost; even the flange material that is scrapped has a higher cost. Plausibly, plate material is available in a greater range of thicknesses, so that a fabricated tee section could be made with dimensions conforming more closely to those of the design shape. Furthermore, material thickness can be more efficiently used to tailor section properties, instead of using flange and web thickness ratios which suit rolling mill production of I-beams.

This program was undertaken to evaluate methods of producing tee shapes for panel stiffening, considering cutting methods, welding methods, as well as the quality and relative economies offered by the various processes. The practice of fabricating structural shapes has been traditionally limited to making only those shapes larger than commercially available, such as web frames in ships and highway bridge beams, among others. Usually, lighter sections have not been considered cost-effective for custom production, due to the wide variety needed, and the estimated labor costs and high distortion produced by the older, more traditional welding methods. Newer welding technologies, such as laser welding and high-frequency resistance welding have challenged these assumptions, but have not made inroads into shipbuilding practice.

Objective

The purpose of this design analysis phase is to determine the potential weight reduction which can be achieved if fabricated Tee shapes are substituted for stripped I-Beams. It is plausible that plates and sheets can be obtained with a greater freedom of choice of material thickness, and therefore, weight, than hot-rolled structural shapes. Since "the next larger" shape than that required by design is selected from the catalog, the final form of the fabricated shape should be more nearly equal to the design requirement, resulting in weight savings with no sacrifice in performance.

Therefore, this phase asked these questions:

- ◆ Can a given population of various Tee shapes for a specific vessel be manufactured from plate with a net savings in weight?
- ◆ What are the savings possible, and will a significant loss of strength result from design tradeoffs?
- ◆ Are there any negative effects which will show the substitution of fabricated shapes to be impracticable or inadvisable?
- ◆ For the stability and performance goals of a given vessel, will the savings in weight of Tee sections have any negative effects?

Approach

To provide a well-understood population of Tee sections for analysis, the DDG-51 class hull was chosen. Currently in production at BIW, this hull uses thirty different Tee shapes which are produced by stripping flanges from I-Beams. In all, more than eighty thousand feet of I-Beams weighing a total of nearly 690 long tons are stripped to yield 519 tons of tee shapes. Scrap from the stripping activity weighs in excess of 170 long tons and represents a significant loss (over $91,000 if purchased at the recent price of $480/short ton). While this scrap is recyclable, the scrap value may not equal the costs of handling for disposal.

Since the loading requirements and performance issues of this vessel are well-known, the specifications and fabrication documents can be used to recreate the design scenario for selected portions of the structure. In contrast with the traditional approach of design with stripped beams, these areas were evaluated for actual section requirements. Then a trial design of a fabricated tee-shape was made, using available thicknesses of plate material. A significant constraint used was that the fabricated shape must conform to the same envelope as the stripped shape it would replace. While restricting the freedom of design for the purpose of weight reduction, this allows the consideration of changing an existing design with minimum impact on outfitting, such as cable runs, pipe hangers and ventilation.

This evaluation was carried out by Brian Miller of BIW’s Structural Engineering department. Mr. Miller’s analysis is contained in Appendix A, “Engineering Evaluation.” To provide a diversity of expression and stimulate thought on the part of the reader, there has been no attempt to editorially change any of the analysis or opinions expressed. In fact, the only comment that this reviewer would add to Mr. Miller’s analysis, is in regards to the effect of stiffener weight reduction on the ship’s vertical center of gravity (VCG). Truly, the mere reduction of stiffener weight across the board should not be made without considering effects on stability. However, if stiffener weight is reduced, the loss of stiffener weight below the VCG could easily be compensated by using thicker plating in the hull below the VCG. This would have the beneficial effect of increasing resistance to damage due to impact or corrosion. Furthermore, tank bulkheads and other structures may be evaluated, and made thicker as needed in these areas. This kind of thought process will be of greatest benefit in a new ship design, if the traditional approach of using the stripped I-beam is questioned at the outset.

TEE BEAM MANUFACTURING ANALYSIS

FOR

WEIGHT REDUCTION AND PRODUCIBILITY

NSRP PROJECT #N7-91-4

APPENDIX B

TO

FINAL REPORT

COST ANALYSIS MATRICES

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October 31, 1994

INTRODUCTION

This section provides detailed matrices of various cost elements which were aggregated into the summaries in the main report. Starting with a list of I/T shapes, individual processing speeds were estimated for each of the I-beam sections in the target group. Cutting speeds were chosen based on manufacturers' literature and other sources, with the "effective thickness" approximated as the total of flange thickness plus one-half the radius. Welding speeds for SAW and GMAW were chosen based on the published data for making fillet welds sized to join the web and flange at 100% weld efficiency. GMAW speeds were based on data provided for metal-cored electrodes, but the speeds would not differ greatly for solid wires or traditional flux-cored wires.

Given the assumptions of travel speeds for each item, the times to process the total length of all of the given pieces of that item were calculated, and the times for all the items were summed for a total processing time for each method.

These processing times were factored into several scenarios of material cost, labor rate, and (for the continuous-process machinery) duty cycle. Batch-process duty cycles were not varied, since the basis of experience shows that the overall processing times associated with batch OFC are fairly constant (based on the SABL data and the studies in this project). Furthermore, since the processing rates for the batch OFC methods were well-known by experience, and since the other processes may not always be used at their optimum speeds, the manufacturer's data for OFC burning speeds was used. This was substantially faster than cutting speeds observed from time to time in production.

Cutting methods had rework added in at the experienced rate for standard OFC. Since the other cutting methods were substantially faster and should give less thermally-induced distortion, rework was approximated at one-half that of the OFC experience. Rework was not factored into the welding scenarios, because experience with continuous-process tee-fabricating machinery has demonstrated the ability to produce acceptable parts without rework. Finally, a standard rate of 4 labor hours per plate (handling and burning) was used to calculate processing time to produce strips for tees from plates. The total of flange and web widths plus kerf was used to estimate the number of plates required, and the scrap produced.

Three groups of production scenarios were generated, in which one cost element (labor, material, or duty cycle) was varied while the other two were held constant. Total cost calculated from these tables were used to generate Tables IV, V, and VI, and Figures 13, 14, and 15 in the main report.

Summary of Tables

- Cutcomp: cutting speeds/times for OFC, Batch PAC, Continuous PAC, and Continuous LBC.
- Weldcomp: welding speeds/times for SAW, GMAW, and LBW.
- Costcmp (1-6): comparative costs for production at varying labor rates, with steel cost and duty cycle constant.
- Costcmp (a-g): comparative costs for production at varying steel prices, with labor rates and duty cycle constant.
- Costcmp (t-z): comparative costs for production at varying duty cycle, with steel cost and labor rates constant.

cutcomp: Cutting times/speeds for OFC, PAC, and LBC

Depth (in)	I #/ft	T #/ft	Lgth ea- (ft)	Qty	Total Feet	Flg Width	Flg Thk	Root Radius	Eff Thk Flg+.5R	OFC Cutting Spd (ipm)	OFC Time/bar Minutes	OFC Process Time (min	PAC Cutting Spd (ipm)	PAC Time/bar Minutes	PAC Process Time (min	LBC Cutting Spd (ipm)	LBC Time/bar Minutes	LBC Process Time (min
8	10	7.48	40	2	80	3.940	0.205	0.300	0.355	28	17.1	34.3	85	5.6	11.3	181	2.7	5.3
10	15	11.64	40	17	680	4.000	0.270	0.300	0.42	27	17.8	302.2	80	6.0	102.0	156	3.1	52.3
8	18	12.92	20	25	500	5.250	0.330	0.300	0.48	27	8.9	222.2	65	3.7	92.3	138	1.7	43.5
6	9	6.43	49	195	9555	3.940	0.215	0.300	0.365	28	21.0	4095.0	85	6.9	1348.9	177	3.3	647.8
8	10	7.48	49	319	15631	3.940	0.205	0.300	0.355	28	21.0	6699.0	85	6.9	2206.7	181	3.2	1036.3
8	13	9.90	49	67	3283	4.000	0.255	0.300	0.405	27	21.8	1459.1	70	8.4	562.8	161	3.7	244.7
10	12	9.49	49	154	7546	3.960	0.210	0.300	0.36	28	21.0	3234.0	85	6.9	1065.3	179	3.3	505.9
10	17	12.89	40	25	1000	4.010	0.330	0.300	0.48	27	17.8	444.4	65	7.4	184.6	138	3.5	87.0
10	19	14.24	49	15	735	4.020	0.395	0.300	0.545	25	23.5	352.8	60	9.8	147.0	122	4.8	72.3
12	14	11.27	49	216	10584	3.970	0.225	0.300	0.375	27	21.8	4704.0	85	6.9	1494.2	173	3.4	734.2
12	16	12.83	49	139	6811	3.990	0.265	0.300	0.415	27	21.8	3027.1	70	8.4	1167.6	157	3.7	520.6
12	19	14.81	49	10	490	4.005	0.350	0.300	0.5	25	23.5	235.2	65	9.0	90.5	133	4.4	44.2
12	22	16.78	49	46	2254	4.030	0.425	0.300	0.575	23	25.6	1176.0	60	9.8	450.8	116	5.1	233.2
12	26	18.24	49	47	2303	6.490	0.380	0.370	0.565	25	23.5	1105.4	60	9.8	460.6	116	5.1	238.2
12	30	21.00	49	24	1176	6.520	0.440	0.370	0.625	23	25.6	613.6	55	10.7	256.6	106	5.5	133.1
12	50	33.25	49	8	392	8.080	0.640	0.600	0.94	21	28.0	224.0	25	23.5	188.2	68	8.6	69.2
14	22	16.85	49	56	2744	5.000	0.335	0.430	0.55	27	21.8	1219.6	60	9.8	548.8	116	5.1	283.9
14	26	19.54	49	64	3136	5.025	0.420	0.430	0.635	23	25.6	1636.2	55	10.7	684.2	102	5.8	368.9
14	34	24.21	49	21	1029	6.745	0.455	0.430	0.67	23	25.6	536.9	55	10.7	224.5	97	6.1	127.3
14	43	29.11	49	24	1176	7.995	0.530	0.600	0.83	22	26.7	641.5	35	16.8	403.2	76	7.7	185.7
14	26	20.13	49	28	1372	5.550	0.345	0.430	0.56	25	23.5	658.6	60	9.8	274.4	114	5.2	144.4
16	31	23.53	49	25	1225	5.525	0.440	0.430	0.655	23	25.6	639.1	55	10.7	267.3	99	5.9	148.5
16	36	26.44	49	10	490	0.430	0.430	0.430	0.645	23	25.6	255.7	55	10.7	106.9	101	5.8	58.2
16	40	28.82	49	9	441	6.995	0.505	0.430	0.72	22	26.7	240.5	45	13.1	117.6	91	6.5	58.2
16	45	32.47	49	2	98	7.035	0.565	0.565	0.8475	21	28.0	56.0	35	16.8	33.6	76	7.7	15.5
16	50	36.03	49	14	686	7.070	0.630	0.430	0.845	21	28.0	392.0	35	16.8	235.2	79	7.4	104.2
18	35	27.12	49	35	1715	6.000	0.425	0.430	0.64	23	25.6	894.8	55	10.7	374.2	101	5.8	203.8
18	40	30.27	49	42	2058	6.015	0.525	0.430	0.74	22	26.7	1122.5	45	13.1	548.8	89	6.6	277.5
18	50	36.48	49	46	2254	7.495	0.570	0.430	0.785	21	28.0	1288.0	40	14.7	676.2	84	7.0	322.0
18	60	43.51	49	13	637	7.555	0.695	0.430	0.91	20	29.4	382.2	30	19.6	254.8	73	8.1	104.7
20	55	44.18	20	18	360	7.005	0.505	0.650	0.83	22	10.9	196.4	35	6.9	123.4	75	3.2	57.6
				1716	82441						Minutes:	38088.2		Minutes:	14702.5		Minutes:	7128.0
											Hours:	634.8		Hours:	245.0		Hours:	118.8
											Shifts:	79.4		Shifts:	30.6		Shifts:	14.8

weldcomp: Welding Time Comparison, SAW, GMAW-MC (metal-core), LBW

Depth (in)	I #/ft	T #/ft	Lgth ea-(ft)	Qty	Total Feet	Web Thk	Flg Thk	Fillet Leg Size in.	SAW Welding Spd (ipm)	SAW Time/bar Minutes	SAW Process Time (min	GMAW Welding Spd (ipm)	GMAW Time/bar Minutes	GMAW Process Time (min	LBW Welding Spd (ipm)	LBW Time/bar Minutes	LBW Process Time (min
8	10	7.48	40	2	80	0.170	0.205	0.125	78	6.2	12.3	50	9.6	19.2	140	3.4	6.9
10	15	11.64	40	17	680	0.230	0.270	0.188	72	6.7	113.3	45	10.7	181.3	112		72.9
8	18	12.92	20	25	500	0.230	0.330	0.188	72	3.3	83.3	45	5.3	133.3	112	2.1	53.6
6	9	6.43	49	195	9555	0.170	0.215	0.125	78	7.5	1470.0	50	11.8	2293.2	140	4.2	819.0
8	10	7.48	49	319	15631	0.170	0.205	0.125	78	7.5	2404.8	50	11.8	3751.4	140	4.2	1339.8
8	13	9.90	49	67	3283	0.230	0.255	0.188	72	8.2	547.2	45	13.1	875.5	112	5.3	351.8
10	12	9.49	49	154	7546	0.190	0.210	0.188	72	8.2	1257.7	45	13.1	2012.3	131	4.5	691.2
10	17	12.89	40	25	1000	0.240	0.330	0.188	72	6.7	166.7	45	10.7	266.7	108	4.4	111.1
10	19	14.24	49	15	735	0.250	0.395	0.188	72	8.2	122.5	45	13.1	196.0	103	5.7	85.6
12	14	11.27	49	216	10584	0.200	0.225	0.188	72	8.2	1764.0	45	13.1	2822.4	126	4.7	1008.0
12	16	12.83	49	139	6811	0.220	0.265	0.188	72	8.2	1135.2	45	13.1	1816.3	117	5.0	698.6
12	19	14.81	49	10	490	0.235	0.350	0.188	72	8.2	81.7	45	13.1	130.7	110	5.3	53.5
12	22	16.78	49	46	2254	0.260	0.425	0.188	72	8.2	375.7	45	13.1	601.1	98	6.0	276.0
12	26	18.24	49	47	2303	0.230	0.380	0.188	72	8.2	383.8	45	13.1	614.1	112	5.3	246.8
12	30	21.00	49	24	1176	0.260	0.440	0.188	72	8.2	196.0	45	13.1	313.6	98	6.0	144.0
12	50	33.25	49	8	392	0.370	0.640	0.250	60	9.8	78.4	35	16.8	134.4	47	12.5	100.1
14	22	16.85	49	56	2744	0.230	0.335	0.188	72	8.2	457.3	45	13.1	731.7	112	5.3	294.0
14	26	19.54	49	64	3136	0.255	0.420	0.188	72	8.2	522.7	45	13.1	836.3	100	5.9	376.3
14	34	24.21	49	21	1029	0.285	0.455	0.188	72	8.2	171.5	45	13.1	274.4	86	6.8	143.6
14	43	29.11	49	24	1176	0.305	0.530	0.250	60	9.8	235.2	35	16.8	403.2	77	7.6	183.3
14	26	20.13	49	28	1372	0.250	0.345	0.188	72	8.2	228.7	45	13.1	365.9	103	5.7	159.8
16	31	23.53	49	25	1225	0.275	0.440	0.188	72	8.2	204.2	45	13.1	326.7	91	6.5	161.5
16	36	26.44	49	10	490	0.295	0.430	0.188	72	8.2	81.7	45	13.1	130.7	87	6.8	67.6
16	40	28.82	49	9	441	0.305	0.505	0.250	60	9.8	88.2	35	16.8	151.2	77	7.6	68.7
16	45	32.47	49	2	98	0.345	0.565	0.250	60	9.8	19.6	35	16.8	33.6	58	10.1	20.3
16	50	36.03	49	14	686	0.380	0.630	0.250	60	9.8	137.2	35	16.8	235.2	42	14.0	196.0
18	35	27.12	49	35	1715	0.300	0.425	0.250	60	9.8	343.0	35	16.8	588.0	79	7.4	260.5
18	40	30.27	49	42	2058	0.315	0.525	0.250	60	9.8	411.6	35	16.8	705.6	72	8.2	343.0
18	50	36.48	49	46	2254	0.355	0.570	0.250	60	9.8	450.8	35	16.8	772.8	54	10.9	500.9
18	60	43.51	49	13	637	0.415	0.695	0.313	48	12.3	159.3	25	23.5	305.8	25	23.5	305.8
20	55	44.18	20	18	360	0.395	0.505	0.313	48	5.0	90.0	25	9.6	172.8	35	6.9	123.4
				1716	82441					Minutes:	13793.3		Minutes:	22195.2		Minutes:	9263.4
										Hours:	229.9		Hours:	369.9		Hours:	154.4
										Shifts:	28.7		Shifts:	46.2		Shifts:	19.3

Note: SAW & GMAW fillet sizes are based on 100% efficiency; LBW speeds are based on 10 kW, full penetration, 50+% from each side.

costcmp1: Cost comparison at 15 $/hr labor cost

	"Standard"	PAC						
	"Batch"	"Batch"	"Continuous"	"Continuous"		"Continuous"	"Continuous"	"Continuous"
	OFC		PAC	LC		SAW	GMAW	LW
Material	I-Beams	I-Beams	I-Beams	I-Beams		Plate strips	Plate strips	Plate strips
Mat'l Wgt, Ltns	690	690	690	690		476	476	476
Mat'l Cost	$340,032.00	$340,032.00	$340,032.00	$340,032.00		$234,572.80	$234,572.80	$234,572.80
Total # Tees	1716	1716	1716	1716		1716	1716	1716
Prep Time (Lhrs)	0	0	0	0		1115	1115	1115
Prep Labor Cost	$0.00	$0.00	$0.00	$0.00		$16,725.00	$16,725.00	$16,725.00
Prep Scrp (5%), LTns	0	0	0	0		23.8	23.8	23.8
Prep Scrap Cost	$0.00	$0.00	$0.00	$0.00		$11,728.64	$11,728.64	$11,728.64
Move to Process, LHrs	489.06	489.06	489.06	489.06		489.06	489.06	489.06
Process, Lhrs	2282.28	2110.68	1031.58	501.05		968.42	1557.89	652.63
Move From Process, Lhrs	489.06	489.06	489.06	489.06		489.06	489.06	489.06
Process Cost	$48,906.00	$46,332.00	$30,145.48	$22,187.59		$29,198.12	$38,040.22	$24,461.27
Process Scrap wgt. Ltns	171	171	171	171		0	0	0
Process Scrap cost	$84,268.80	$84,268.80	$84,268.80	$84,268.80		0	0	0
Rework, LHrs	978.12	480.48	480.48	480.48		0.00	0.00	0.00
Rework Cost	$14,671.80	$7,207.20	$7,207.20	$7,207.20		$0.00	$0.00	$0.00
Total Cost	$403,609.80	$393,571.20	$377,384.68	$369,426.79		$280,495.92	$289,338.02	$275,759.07
Material Cost:	$0.22	$0.22	$0.22	$0.22		$0.22	$0.22	$0.22
Labor Rate:	$15.00	$15.00	$15.00	$15.00		$15.00	$15.00	$15.00
Machine Duty Cycle:	1.00	1.00	0.95	0.95		0.95	0.95	0.95

costcmp2: Cost comparison at 20 $/hr labor cost

	"Standard"	PAC						
	"Batch"	"Batch"	"Continuous"	"Continuous"		"Continuous"	"Continuous"	"Continuous"
	OFC		PAC	LC		SAW	GMAW	LW
Material	I-Beams	I-Beams	I-Beams	I-Beams		Plate strips	Plate strips	Plate strips
Mat'l Wgt, Ltns	690	690	690	690		476	476	476
Mat'l Cost	$340,032.00	$340,032.00	$340,032.00	$340,032.00		$234,572.80	$234,572.80	$234,572.80
Total # Tees	1716	1716	1716	1716		1716	1716	1716
Prep Time (Lhrs)	0	0	0	0		1115	1115	1115
Prep Labor Cost	$0.00	$0.00	$0.00	$0.00		$22,300.00	$22,300.00	$22,300.00
Prep Scrp (5%), LTns	0	0	0	0		23.8	23.8	23.8
Prep Scrap Cost	$0.00	$0.00	$0.00	$0.00		$11,728.64	$11,728.64	$11,728.64
Move to Process, LHrs	489.06	489.06	489.06	489.06		489.06	489.06	489.06
Process, Lhrs	2282.28	2110.68	1031.58	501.05		968.42	1557.89	652.63
Move From Process, Lhrs	489.06	489.06	489.06	489.06		489.06	489.06	489.06
Process Cost	$65,208.00	$61,776.00	$40,193.98	$29,583.45		$38,930.82	$50,720.29	$32,615.03
Process Scrap wgt. Ltns	171	171	171	171		0	0	0
Process Scrap cost	$84,268.80	$84,268.80	$84,268.80	$84,268.80		0	0	0
Rework, LHrs	978.12	480.48	480.48	480.48		0.00	0.00	0.00
Rework Cost	$19,562.40	$9,609.60	$9,609.60	$9,609.60		$0.00	$0.00	$0.00
Total Cost	$424,802.40	$411,417.60	$389,835.58	$379,225.05		$295,803.62	$307,593.09	$289,487.83
Material Cost:	$0.22	$0.22	$0.22	$0.22		$0.22	$0.22	$0.22
Labor Rate:	$20.00	$20.00	$20.00	$20.00		$20.00	$20.00	$20.00
Machine Duty Cycle:	1.00	1.00	0.95	0.95		0.95	0.95	0.95

costcmp3: Cost comparison at 25 $/hr labor cost

	"Standard" "Batch" OFC	PAC "Batch"	"Continuous" PAC	"Continuous" LC		"Continuous" SAW	"Continuous" GMAW	"Continuous" LW
Material	I-Beams	I-Beams	I-Beams	I-Beams		Plate strips	Plate strips	Plate strips
Mat'l Wgt, Ltns	690	690	690	690		476	476	476
Mat'l Cost	$340,032.00	$340,032.00	$340,032.00	$340,032.00		$234,572.80	$234,572.80	$234,572.80
Total # Tees	1716	1716	1716	1716		1716	1716	1716
Prep Time (Lhrs)	0	0	0	0		1115	1115	1115
Prep Labor Cost	$0.00	$0.00	$0.00	$0.00		$27,875.00	$27,875.00	$27,875.00
Prep Scrp (5%), LTns	0	0	0	0		23.8	23.8	23.8
Prep Scrap Cost	$0.00	$0.00	$0.00	$0.00		$11,728.64	$11,728.64	$11,728.64
Move to Process, LHrs	489.06	489.06	489.06	489.06		489.06	489.06	489.06
Process, Lhrs	2282.28	2110.68	1031.58	501.05		968.42	1557.89	652.63
Move From Process, Lhrs	489.06	489.06	489.06	489.06		489.06	489.06	489.06
Process Cost	$81,510.00	$77,220.00	$50,242.47	$36,979.32		$48,663.53	$63,400.37	$40,768.79
Process Scrap wgt. Ltns	171	171	171	171		0	0	0
Process Scrap cost	$84,268.80	$84,268.80	$84,268.80	$84,268.80		0	0	0
Rework, LHrs	978.12	480.48	480.48	480.48		0.00	0.00	0.00
Rework Cost	$24,453.00	$12,012.00	$12,012.00	$12,012.00		$0.00	$0.00	$0.00
Total Cost	$445,995.00	$429,264.00	$402,286.47	$389,023.32		$311,111.33	$325,848.17	$303,216.59
Material Cost:	$0.22	$0.22	$0.22	$0.22		$0.22	$0.22	$0.22
Labor Rate:	$25.00	$25.00	$25.00	$25.00		$25.00	$25.00	$25.00
Machine Duty Cycle:	1.00	1.00	0.95	0.95		0.95	0.95	0.95

costcmp4: Cost comparison at 30 $/hr labor cost

	"Standard" "Batch" OFC	PAC "Batch"	"Continuous" PAC	"Continuous" LC		"Continuous" SAW	"Continuous" GMAW	"Continuous" LW
Material	I-Beams	I-Beams	I-Beams	I-Beams		Plate strips	Plate strips	Plate strips
Mat'l Wgt, Ltns	690	690	690	690		476	476	476
Mat'l Cost	$340,032.00	$340,032.00	$340,032.00	$340,032.00		$234,572.80	$234,572.80	$234,572.80
Total # Tees	1716	1716	1716	1716		1716	1716	1716
Prep Time (Lhrs)	0	0	0	0		1115	1115	1115
Prep Labor Cost	$0.00	$0.00	$0.00	$0.00		$33,450.00	$33,450.00	$33,450.00
Prep Scrp (5%), LTns	0	0	0	0		23.8	23.8	23.8
Prep Scrap Cost	$0.00	$0.00	$0.00	$0.00		$11,728.64	$11,728.64	$11,728.64
Move to Process, LHrs	489.06	489.06	489.06	489.06		489.06	489.06	489.06
Process, Lhrs	2282.28	2110.68	1031.58	501.05		968.42	1557.89	652.63
Move From Process, Lhrs	489.06	489.06	489.06	489.06		489.06	489.06	489.06
Process Cost	$97,812.00	$92,664.00	$60,290.97	$44,375.18		$58,396.23	$76,080.44	$48,922.55
Process Scrap wgt. Ltns	171	171	171	171		0	0	0
Process Scrap cost	$84,268.80	$84,268.80	$84,268.80	$84,268.80		0	0	0
Rework, LHrs	978.12	480.48	480.48	480.48		0.00	0.00	0.00
Rework Cost	$29,343.60	$14,414.40	$14,414.40	$14,414.40		$0.00	$0.00	$0.00
Total Cost	$467,187.60	$447,110.40	$414,737.37	$398,821.58		$326,419.03	$344,103.24	$316,945.35
Material Cost:	$0.22	$0.22	$0.22	$0.22		$0.22	$0.22	$0.22
Labor Rate:	$30.00	$30.00	$30.00	$30.00		$30.00	$30.00	$30.00
Machine Duty Cycle:	1.00	1.00	0.95	0.95		0.95	0.95	0.95

costcmp5: Cost comparison at 35 $/hr labor cost

	"Standard"	PAC						
	"Batch"	"Batch"	"Continuous"	"Continuous"		"Continuous"	"Continuous"	"Continuous"
	OFC		PAC	LC		SAW	GMAW	LW
Material	I-Beams	I-Beams	I-Beams	I-Beams		Plate strips	Plate strips	Plate strips
Mat'l Wgt, Ltns	690	690	690	690		476	476	476
Mat'l Cost	$340,032.00	$340,032.00	$340,032.00	$340,032.00		$234,572.80	$234,572.80	$234,572.80
Total # Tees	1716	1716	1716	1716		1716	1716	1716
Prep Time (Lhrs)	0	0	0	0		1115	1115	1115
Prep Labor Cost	$0.00	$0.00	$0.00	$0.00		$39,025.00	$39,025.00	$39,025.00
Prep Scrp (5%), LTns	0	0	0	0		23.8	23.8	23.8
Prep Scrap Cost	$0.00	$0.00	$0.00	$0.00		$11,728.64	$11,728.64	$11,728.64
Move to Process, LHrs	489.06	489.06	489.06	489.06		489.06	489.06	489.06
Process, Lhrs	2282.28	2110.68	1031.58	501.05		968.42	1557.89	652.63
Move From Process, Lhrs	489.06	489.06	489.06	489.06		489.06	489.06	489.06
Process Cost	$114,114.00	$108,108.00	$70,339.46	$51,771.04		$68,128.94	$88,760.52	$57,076.31
Process Scrap wgt. Ltns	171	171	171	171		0	0	0
Process Scrap cost	$84,268.80	$84,268.80	$84,268.80	$84,268.80		0	0	0
Rework, LHrs	978.12	480.48	480.48	480.48		0.00	0.00	0.00
Rework Cost	$34,234.20	$16,816.80	$16,816.80	$16,816.80		$0.00	$0.00	$0.00
Total Cost	$488,380.20	$464,956.80	$427,188.26	$408,619.84		$341,726.74	$362,358.32	$330,674.11
Material Cost:	$0.22	$0.22	$0.22	$0.22		$0.22	$0.22	$0.22
Labor Rate:	$35.00	$35.00	$35.00	$35.00		$35.00	$35.00	$35.00
Machine Duty Cycle:	1.00	1.00	0.95	0.95		0.95	0.95	0.95

costcmp6: Cost comparison at 40 $/hr labor cost

	"Standard"	PAC						
	"Batch"	"Batch"	"Continuous"	"Continuous"		"Continuous"	"Continuous"	"Continuous"
	OFC		PAC	LC		SAW	GMAW	LW
Material	I-Beams	I-Beams	I-Beams	I-Beams		Plate strips	Plate strips	Plate strips
Mat'l Wgt, Ltns	690	690	690	690		476	476	476
Mat'l Cost	$340,032.00	$340,032.00	$340,032.00	$340,032.00		$234,572.80	$234,572.80	$234,572.80
Total # Tees	1716	1716	1716	1716		1716	1716	1716
Prep Time (Lhrs)	0	0	0	0		1115	1115	1115
Prep Labor Cost	$0.00	$0.00	$0.00	$0.00		$44,600.00	$44,600.00	$44,600.00
Prep Scrp (5%), LTns	0	0	0	0		23.8	23.8	23.8
Prep Scrap Cost	$0.00	$0.00	$0.00	$0.00		$11,728.64	$11,728.64	$11,728.64
Move to Process, LHrs	489.06	489.06	489.06	489.06		489.06	489.06	489.06
Process, Lhrs	2282.28	2110.68	1031.58	501.05		968.42	1557.89	652.63
Move From Process, Lhrs	489.06	489.06	489.06	489.06		489.06	489.06	489.06
Process Cost	$130,416.00	$123,552.00	$80,387.96	$59,166.91		$77,861.64	$101,440.59	$65,230.06
Process Scrap wgt. Ltns	171	171	171	171		0	0	0
Process Scrap cost	$84,268.80	$84,268.80	$84,268.80	$84,268.80		0	0	0
Rework, LHrs	978.12	480.48	480.48	480.48		0.00	0.00	0.00
Rework Cost	$39,124.80	$19,219.20	$19,219.20	$19,219.20		$0.00	$0.00	$0.00
Total Cost	$509,572.80	$482,803.20	$439,639.16	$418,418.11		$357,034.44	$380,613.39	$344,402.86
Material Cost:	$0.22	$0.22	$0.22	$0.22		$0.22	$0.22	$0.22
Labor Rate:	$40.00	$40.00	$40.00	$40.00		$40.00	$40.00	$40.00
Machine Duty Cycle:	1.00	1.00	0.95	0.95		0.95	0.95	0.95

costcmpa: Cost comparison at 0.18 $/lb steel cost

	"Standard"	PAC						
	"Batch"	"Batch"	"Continuous"	"Continuous"		"Continuous"	"Continuous"	"Continuous"
	OFC		PAC	LC		SAW	GMAW	LW
Material	I-Beams	I-Beams	I-Beams	I-Beams		Plate strips	Plate strips	Plate strips
Mat'l Wgt, Ltns	690	690	690	690		476	476	476
Mat'l Cost	$278,208.00	$278,208.00	$278,208.00	$278,208.00		$191,923.20	$191,923.20	$191,923.20
Total # Tees	1716	1716	1716	1716		1716	1716	1716
Prep Time (Lhrs)	0	0	0	0		1115	1115	1115
Prep Labor Cost	$0.00	$0.00	$0.00	$0.00		$39,025.00	$39,025.00	$39,025.00
Prep Scrp (5%), LTns	0	0	0	0		23.8	23.8	23.8
Prep Scrap Cost	$0.00	$0.00	$0.00	$0.00		$9,596.16	$9,596.16	$9,596.16
Move to Process, LHrs	489.06	489.06	489.06	489.06		489.06	489.06	489.06
Process, Lhrs	2282.28	2110.68	1031.58	501.05		968.42	1557.89	652.63
Move From Process, Lhrs	489.06	489.06	489.06	489.06		489.06	489.06	489.06
Process Cost	$114,114.00	$108,108.00	$70,339.46	$51,771.04		$68,128.94	$88,760.52	$57,076.31
Process Scrap wgt. Ltns	171	171	171	171		0	0	0
Process Scrap cost	$84,268.80	$84,268.80	$84,268.80	$84,268.80		0	0	0
Rework, LHrs	978.12	480.48	480.48	480.48		0.00	0.00	0.00
Rework Cost	$34,234.20	$16,816.80	$16,816.80	$16,816.80		$0.00	$0.00	$0.00
Total Cost	$426,556.20	$403,132.80	$365,364.26	$346,795.84		$299,077.14	$319,708.72	$288,024.51
Material Cost:	$0.18	$0.18	$0.18	$0.18		$0.18	$0.18	$0.18
Labor Rate:	$35.00	$35.00	$35.00	$35.00		$35.00	$35.00	$35.00
Machine Duty Cycle:	1.00	1.00	0.95	0.95		0.95	0.95	0.95

costcmpb: Cost comparison at 0.20 $/lb steel cost

	"Standard" "Batch" OFC	PAC "Batch"	"Continuous" PAC	"Continuous" LC		"Continuous" SAW	"Continuous" GMAW	"Continuous" LW
Material	I-Beams	I-Beams	I-Beams	I-Beams		Plate strips	Plate strips	Plate strips
Mat'l Wgt, Ltns	690	690	690	690		476	476	476
Mat'l Cost	$309,120.00	$309,120.00	$309,120.00	$309,120.00		$213,248.00	$213,248.00	$213,248.00
Total # Tees	1716	1716	1716	1716		1716	1716	1716
Prep Time (Lhrs)	0	0	0	0		1115	1115	1115
Prep Labor Cost	$0.00	$0.00	$0.00	$0.00		$39,025.00	$39,025.00	$39,025.00
Prep Scrp (5%), LTns	0	0	0	0		23.8	23.8	23.8
Prep Scrap Cost	$0.00	$0.00	$0.00	$0.00		$10,662.40	$10,662.40	$10,662.40
Move to Process, LHrs	489.06	489.06	489.06	489.06		489.06	489.06	489.06
Process, Lhrs	2282.28	2110.68	1031.58	501.05		968.42	1557.89	652.63
Move From Process, Lhrs	489.06	489.06	489.06	489.06		489.06	489.06	489.06
Process Cost	$114,114.00	$108,108.00	$70,339.46	$51,771.04		$68,128.94	$88,760.52	$57,076.31
Process Scrap wgt. Ltns	171	171	171	171		0	0	0
Process Scrap cost	$84,268.80	$84,268.80	$84,268.80	$84,268.80		0	0	0
Rework, LHrs	978.12	480.48	480.48	480.48		0.00	0.00	0.00
Rework Cost	$34,234.20	$16,816.80	$16,816.80	$16,816.80		$0.00	$0.00	$0.00
Total Cost	$457,468.20	$434,044.80	$396,276.26	$377,707.84		$320,401.94	$341,033.52	$309,349.31
Material Cost:	$0.20	$0.20	$0.20	$0.20		$0.20	$0.20	$0.20
Labor Rate:	$35.00	$35.00	$35.00	$35.00		$35.00	$35.00	$35.00
Machine Duty Cycle:	1.00	1.00	0.95	0.95		0.95	0.95	0.95

costcmpc: Cost comparison at 0.22 $/lb steel cost

	"Standard" "Batch" OFC	PAC "Batch"	"Continuous" PAC	"Continuous" LC		"Continuous" SAW	"Continuous" GMAW	"Continuous" LW
Material	I-Beams	I-Beams	I-Beams	I-Beams		Plate strips	Plate strips	Plate strips
Mat'l Wgt, Ltns	690	690	690	690		476	476	476
Mat'l Cost	$340,032.00	$340,032.00	$340,032.00	$340,032.00		$234,572.80	$234,572.80	$234,572.80
Total # Tees	1716	1716	1716	1716		1716	1716	1716
Prep Time (Lhrs)	0	0	0	0		1115	1115	1115
Prep Labor Cost	$0.00	$0.00	$0.00	$0.00		$39,025.00	$39,025.00	$39,025.00
Prep Scrp (5%), LTns	0	0	0	0		23.8	23.8	23.8
Prep Scrap Cost	$0.00	$0.00	$0.00	$0.00		$11,728.64	$11,728.64	$11,728.64
Move to Process, LHrs	489.06	489.06	489.06	489.06		489.06	489.06	489.06
Process, Lhrs	2282.28	2110.68	1031.58	501.05		968.42	1557.89	652.63
Move From Process, Lhrs	489.06	489.06	489.06	489.06		489.06	489.06	489.06
Process Cost	$114,114.00	$108,108.00	$70,339.46	$51,771.04		$68,128.94	$88,760.52	$57,076.31
Process Scrap wgt. Ltns	171	171	171	171		0	0	0
Process Scrap cost	$84,268.80	$84,268.80	$84,268.80	$84,268.80		0	0	0
Rework, LHrs	978.12	480.48	480.48	480.48		0.00	0.00	0.00
Rework Cost	$34,234.20	$16,816.80	$16,816.80	$16,816.80		$0.00	$0.00	$0.00
Total Cost	$488,380.20	$464,956.80	$427,188.26	$408,619.84		$341,726.74	$362,358.32	$330,674.11
Material Cost:	$0.22	$0.22	$0.22	$0.22		$0.22	$0.22	$0.22
Labor Rate:	$35.00	$35.00	$35.00	$35.00		$35.00	$35.00	$35.00
Machine Duty Cycle:	1.00	1.00	0.95	0.95		0.95	0.95	0.95

costcmpd: Cost comparison at 0.24 $/lb steel cost

	"Standard"	PAC						
	"Batch"	"Batch"	"Continuous"	"Continuous"		"Continuous"	"Continuous"	"Continuous"
	OFC		PAC	LC		SAW	GMAW	LW
Material	I-Beams	I-Beams	I-Beams	I-Beams		Plate strips	Plate strips	Plate strips
Mat'l Wgt, Ltns	690	690	690	690		476	476	476
Mat'l Cost	$370,944.00	$370,944.00	$370,944.00	$370,944.00		$255,897.60	$255,897.60	$255,897.60
Total # Tees	1716	1716	1716	1716		1716	1716	1716
Prep Time (Lhrs)	0	0	0	0		1115	1115	1115
Prep Labor Cost	$0.00	$0.00	$0.00	$0.00		$39,025.00	$39,025.00	$39,025.00
Prep Scrp (5%), LTns	0	0	0	0		23.8	23.8	23.8
Prep Scrap Cost	$0.00	$0.00	$0.00	$0.00		$12,794.88	$12,794.88	$12,794.88
Move to Process, LHrs	489.06	489.06	489.06	489.06		489.06	489.06	489.06
Process, Lhrs	2282.28	2110.68	1031.58	501.05		968.42	1557.89	652.63
Move From Process, Lhrs	489.06	489.06	489.06	489.06		489.06	489.06	489.06
Process Cost	$114,114.00	$108,108.00	$70,339.46	$51,771.04		$68,128.94	$88,760.52	$57,076.31
Process Scrap wgt. Ltns	171	171	171	171		0	0	0
Process Scrap cost	$84,268.80	$84,268.80	$84,268.80	$84,268.80		0	0	0
Rework, LHrs	978.12	480.48	480.48	480.48		0.00	0.00	0.00
Rework Cost	$34,234.20	$16,816.80	$16,816.80	$16,816.80		$0.00	$0.00	$0.00
Total Cost	$519,292.20	$495,868.80	$458,100.26	$439,531.84		$363,051.54	$383,683.12	$351,998.91
Material Cost:	$0.24	$0.24	$0.24	$0.24		$0.24	$0.24	$0.24
Labor Rate:	$35.00	$35.00	$35.00	$35.00		$35.00	$35.00	$35.00
Machine Duty Cycle:	1.00	1.00	0.95	0.95		0.95	0.95	0.95

costcmpe: Cost comparison at 0.26 $/lb steel cost

	"Standard" "Batch" OFC	PAC "Batch"	"Continuous" PAC	"Continuous" LC		"Continuous" SAW	"Continuous" GMAW	"Continuous" LW
Material	I-Beams	I-Beams	I-Beams	I-Beams		Plate strips	Plate strips	Plate strips
Mat'l Wgt, Ltns	690	690	690	690		476	476	476
Mat'l Cost	$401,856.00	$401,856.00	$401,856.00	$401,856.00		$277,222.40	$277,222.40	$277,222.40
Total # Tees	1716	1716	1716	1716		1716	1716	1716
Prep Time (Lhrs)	0	0	0	0		1115	1115	1115
Prep Labor Cost	$0.00	$0.00	$0.00	$0.00		$39,025.00	$39,025.00	$39,025.00
Prep Scrp (5%), LTns	0	0	0	0		23.8	23.8	23.8
Prep Scrap Cost	$0.00	$0.00	$0.00	$0.00		$13,861.12	$13,861.12	$13,861.12
Move to Process, LHrs	489.06	489.06	489.06	489.06		489.06	489.06	489.06
Process, Lhrs	2282.28	2110.68	1031.58	501.05		968.42	1557.89	652.63
Move From Process, Lhrs	489.06	489.06	489.06	489.06		489.06	489.06	489.06
Process Cost	$114,114.00	$108,108.00	$70,339.46	$51,771.04		$68,128.94	$88,760.52	$57,076.31
Process Scrap wgt. Ltns	171	171	171	171		0	0	0
Process Scrap cost	$84,268.80	$84,268.80	$84,268.80	$84,268.80		0	0	0
Rework, LHrs	978.12	480.48	480.48	480.48		0.00	0.00	0.00
Rework Cost	$34,234.20	$16,816.80	$16,816.80	$16,816.80		$0.00	$0.00	$0.00
Total Cost	$550,204.20	$526,780.80	$489,012.26	$470,443.84		$384,376.34	$405,007.92	$373,323.71
Material Cost:	$0.26	$0.26	$0.26	$0.26		$0.26	$0.26	$0.26
Labor Rate:	$35.00	$35.00	$35.00	$35.00		$35.00	$35.00	$35.00
Machine Duty Cycle:	1.00	1.00	0.95	0.95		0.95	0.95	0.95

costcmpf: Cost comparison at 0.28 $/lb steel cost

	"Standard"	PAC						
	"Batch"	"Batch"	"Continuous"	"Continuous"		"Continuous"	"Continuous"	"Continuous"
	OFC		PAC	LC		SAW	GMAW	LW
Material	I-Beams	I-Beams	I-Beams	I-Beams		Plate strips	Plate strips	Plate strips
Mat'l Wgt, Ltns	690	690	690	690		476	476	476
Mat'l Cost	$432,768.00	$432,768.00	$432,768.00	$432,768.00		$298,547.20	$298,547.20	$298,547.20
Total # Tees	1716	1716	1716	1716		1716	1716	1716
Prep Time (Lhrs)	0	0	0	0		1115	1115	1115
Prep Labor Cost	$0.00	$0.00	$0.00	$0.00		$39,025.00	$39,025.00	$39,025.00
Prep Scrp (5%), LTns	0	0	0	0		23.8	23.8	23.8
Prep Scrap Cost	$0.00	$0.00	$0.00	$0.00		$14,927.36	$14,927.36	$14,927.36
Move to Process, LHrs	489.06	489.06	489.06	489.06		489.06	489.06	489.06
Process, Lhrs	2282.28	2110.68	1031.58	501.05		968.42	1557.89	652.63
Move From Process, Lhrs	489.06	489.06	489.06	489.06		489.06	489.06	489.06
Process Cost	$114,114.00	$108,108.00	$70,339.46	$51,771.04		$68,128.94	$88,760.52	$57,076.31
Process Scrap wgt. Ltns	171	171	171	171		0	0	0
Process Scrap cost	$84,268.80	$84,268.80	$84,268.80	$84,268.80		0	0	0
Rework, LHrs	978.12	480.48	480.48	480.48		0.00	0.00	0.00
Rework Cost	$34,234.20	$16,816.80	$16,816.80	$16,816.80		$0.00	$0.00	$0.00
Total Cost	$581,116.20	$557,692.80	$519,924.26	$501,355.84		$405,701.14	$426,332.72	$394,648.51
Material Cost:	$0.28	$0.28	$0.28	$0.28		$0.28	$0.28	$0.28
Labor Rate:	$35.00	$35.00	$35.00	$35.00		$35.00	$35.00	$35.00
Machine Duty Cycle:	1.00	1.00	0.95	0.95		0.95	0.95	0.95

costcmpg: Cost comparison at 0.30 $/lb steel cost

	"Standard"	PAC						
	"Batch"	"Batch"	"Continuous"	"Continuous"		"Continuous"	"Continuous"	"Continuous"
	OFC		PAC	LC		SAW	GMAW	LW
Material	I-Beams	I-Beams	I-Beams	I-Beams		Plate strips	Plate strips	Plate strips
Mat'l Wgt, Ltns	690	690	690	690		476	476	476
Mat'l Cost	$463,680.00	$463,680.00	$463,680.00	$463,680.00		$319,872.00	$319,872.00	$319,872.00
Total # Tees	1716	1716	1716	1716		1716	1716	1716
Prep Time (Lhrs)	0	0	0	0		1115	1115	1115
Prep Labor Cost	$0.00	$0.00	$0.00	$0.00		$39,025.00	$39,025.00	$39,025.00
Prep Scrp (5%), LTns	0	0	0	0		23.8	23.8	23.8
Prep Scrap Cost	$0.00	$0.00	$0.00	$0.00		$15,993.60	$15,993.60	$15,993.60
Move to Process, LHrs	489.06	489.06	489.06	489.06		489.06	489.06	489.06
Process, Lhrs	2282.28	2110.68	1031.58	501.05		968.42	1557.89	652.63
Move From Process, Lhrs	489.06	489.06	489.06	489.06		489.06	489.06	489.06
Process Cost	$114,114.00	$108,108.00	$70,339.46	$51,771.04		$68,128.94	$88,760.52	$57,076.31
Process Scrap wgt. Ltns	171	171	171	171		0	0	0
Process Scrap cost	$84,268.80	$84,268.80	$84,268.80	$84,268.80		0	0	0
Rework, LHrs	978.12	480.48	480.48	480.48		0.00	0.00	0.00
Rework Cost	$34,234.20	$16,816.80	$16,816.80	$16,816.80		$0.00	$0.00	$0.00
Total Cost	$612,028.20	$588,604.80	$550,836.26	$532,267.84		$427,025.94	$447,657.52	$415,973.31
Material Cost:	$0.30	$0.30	$0.30	$0.30		$0.30	$0.30	$0.30
Labor Rate:	$35.00	$35.00	$35.00	$35.00		$35.00	$35.00	$35.00
Machine Duty Cycle:	1.00	1.00	0.95	0.95		0.95	0.95	0.95

costcmpt: Cost comparison at 50% machine utilization (ex. all "batch" at 100%)

	"Standard"	PAC						
	"Batch"	"Batch"	"Continuous"	"Continuous"		"Continuous"	"Continuous"	"Continuous"
	OFC		PAC	LC		SAW	GMAW	LW
Material	I-Beams	I-Beams	I-Beams	I-Beams		Plate strips	Plate strips	Plate strips
Mat'l Wgt, Ltns	690	690	690	690		476	476	476
Mat'l Cost	$340,032.00	$340,032.00	$340,032.00	$340,032.00		$234,572.80	$234,572.80	$234,572.80
Total # Tees	1716	1716	1716	1716		1716	1716	1716
Prep Time (Lhrs)	0	0	0	0		1115	1115	1115
Prep Labor Cost	$0.00	$0.00	$0.00	$0.00		$39,025.00	$39,025.00	$39,025.00
Prep Scrp (5%), LTns	0	0	0	0		23.8	23.8	23.8
Prep Scrap Cost	$0.00	$0.00	$0.00	$0.00		$11,728.64	$11,728.64	$11,728.64
Move to Process, LHrs	489.06	489.06	489.06	489.06		489.06	489.06	489.06
Process, Lhrs	2282.28	2110.68	1960.00	952.00		1840.00	2960.00	1240.00
Move From Process, Lhrs	489.06	489.06	489.06	489.06		489.06	489.06	489.06
Process Cost	$114,114.00	$108,108.00	$102,834.20	$67,554.20		$98,634.20	$137,834.20	$77,634.20
Process Scrap wgt. Ltns	171	171	171	171		0	0	0
Process Scrap cost	$84,268.80	$84,268.80	$84,268.80	$84,268.80		0	0	0
Rework, LHrs	978.12	480.48	480.48	480.48		0.00	0.00	0.00
Rework Cost	$34,234.20	$16,816.80	$16,816.80	$16,816.80		$0.00	$0.00	$0.00
Total Cost	$488,380.20	$464,956.80	$459,683.00	$424,403.00		$372,232.00	$411,432.00	$351,232.00
Material Cost:	$0.22	$0.22	$0.22	$0.22		$0.22	$0.22	$0.22
Labor Rate:	$35.00	$35.00	$35.00	$35.00		$35.00	$35.00	$35.00
Machine Duty Cycle:	1.00	1.00	0.50	0.50		0.50	0.50	0.50

costcmpu: Cost comparison at 60% machine utilization (ex. all "batch" at 100%)

	"Standard" "Batch" OFC	PAC "Batch"	"Continuous" PAC	"Continuous" LC		"Continuous" SAW	"Continuous" GMAW	"Continuous" LW
Material	I-Beams	I-Beams	I-Beams	I-Beams		Plate strips	Plate strips	Plate strips
Mat'l Wgt, Ltns	690	690	690	690		476	476	476
Mat'l Cost	$340,032.00	$340,032.00	$340,032.00	$340,032.00		$234,572.80	$234,572.80	$234,572.80
Total # Tees	1716	1716	1716	1716		1716	1716	1716
Prep Time (Lhrs)	0	0	0	0		1115	1115	1115
Prep Labor Cost	$0.00	$0.00	$0.00	$0.00		$39,025.00	$39,025.00	$39,025.00
Prep Scrp (5%), LTns	0	0	0	0		23.8	23.8	23.8
Prep Scrap Cost	$0.00	$0.00	$0.00	$0.00		$11,728.64	$11,728.64	$11,728.64
Move to Process, LHrs	489.06	489.06	489.06	489.06		489.06	489.06	489.06
Process, Lhrs	2282.28	2110.68	1633.33	793.33		1533.33	2466.67	1033.33
Move From Process, Lhrs	489.06	489.06	489.06	489.06		489.06	489.06	489.06
Process Cost	$114,114.00	$108,108.00	$91,400.87	$62,000.87		$87,900.87	$120,567.53	$70,400.87
Process Scrap wgt. Ltns	171	171	171	171		0	0	0
Process Scrap cost	$84,268.80	$84,268.80	$84,268.80	$84,268.80		0	0	0
Rework, LHrs	978.12	480.48	480.48	480.48		0.00	0.00	0.00
Rework Cost	$34,234.20	$16,816.80	$16,816.80	$16,816.80		$0.00	$0.00	$0.00
Total Cost	$488,380.20	$464,956.80	$448,249.67	$418,849.67		$361,498.67	$394,165.33	$343,998.67
Material Cost:	$0.22	$0.22	$0.22	$0.22		$0.22	$0.22	$0.22
Labor Rate:	$35.00	$35.00	$35.00	$35.00		$35.00	$35.00	$35.00
Machine Duty Cycle:	1.00	1.00	0.60	0.60		0.60	0.60	0.60

costcmpv: Cost comparison at 75% machine utilization (ex. all "batch" at 100%)

	"Standard"	PAC						
	"Batch"	"Batch"	"Continuous"	"Continuous"		"Continuous"	"Continuous"	"Continuous"
	OFC		PAC	LC		SAW	GMAW	LW
Material	I-Beams	I-Beams	I-Beams	I-Beams		Plate strips	Plate strips	Plate strips
Mat'l Wgt, Ltns	690	690	690	690		476	476	476
Mat'l Cost	$340,032.00	$340,032.00	$340,032.00	$340,032.00		$234,572.80	$234,572.80	$234,572.80
Total # Tees	1716	1716	1716	1716		1716	1716	1716
Prep Time (Lhrs)	0	0	0	0		1115	1115	1115
Prep Labor Cost	$0.00	$0.00	$0.00	$0.00		$39,025.00	$39,025.00	$39,025.00
Prep Scrp (5%), LTns	0	0	0	0		23.8	23.8	23.8
Prep Scrap Cost	$0.00	$0.00	$0.00	$0.00		$11,728.64	$11,728.64	$11,728.64
Move to Process, LHrs	489.06	489.06	489.06	489.06		489.06	489.06	489.06
Process, Lhrs	2282.28	2110.68	1306.67	634.67		1226.67	1973.33	826.67
Move From Process, Lhrs	489.06	489.06	489.06	489.06		489.06	489.06	489.06
Process Cost	$114,114.00	$108,108.00	$79,967.53	$56,447.53		$77,167.53	$103,300.87	$63,167.53
Process Scrap wgt. Ltns	171	171	171	171		0	0	0
Process Scrap cost	$84,268.80	$84,268.80	$84,268.80	$84,268.80		0	0	0
Rework, LHrs	978.12	480.48	480.48	480.48		0.00	0.00	0.00
Rework Cost	$34,234.20	$16,816.80	$16,816.80	$16,816.80		$0.00	$0.00	$0.00
Total Cost	$488,380.20	$464,956.80	$436,816.33	$413,296.33		$350,765.33	$376,898.67	$336,765.33
Material Cost:	$0.22	$0.22	$0.22	$0.22		$0.22	$0.22	$0.22
Labor Rate:	$35.00	$35.00	$35.00	$35.00		$35.00	$35.00	$35.00
Machine Duty Cycle:	1.00	1.00	0.75	0.75		0.75	0.75	0.75

costcmpw: Cost comparison at 80% machine utilization (ex. all "batch" at 100%)

	"Standard"	PAC						
	"Batch"	"Batch"	"Continuous"	"Continuous"		"Continuous"	"Continuous"	"Continuous"
	OFC		PAC	LC		SAW	GMAW	LW
Material	I-Beams	I-Beams	I-Beams	I-Beams		Plate strips	Plate strips	Plate strips
Mat'l Wgt, Ltns	690	690	690	690		476	476	476
Mat'l Cost	$340,032.00	$340,032.00	$340,032.00	$340,032.00		$234,572.80	$234,572.80	$234,572.80
Total # Tees	1716	1716	1716	1716		1716	1716	1716
Prep Time (Lhrs)	0	0	0	0		1115	1115	1115
Prep Labor Cost	$0.00	$0.00	$0.00	$0.00		$39,025.00	$39,025.00	$39,025.00
Prep Scrp (5%), LTns	0	0	0	0		23.8	23.8	23.8
Prep Scrap Cost	$0.00	$0.00	$0.00	$0.00		$11,728.64	$11,728.64	$11,728.64
Move to Process, LHrs	489.06	489.06	489.06	489.06		489.06	489.06	489.06
Process, Lhrs	2282.28	2110.68	1225.00	595.00		1150.00	1850.00	775.00
Move From Process, Lhrs	489.06	489.06	489.06	489.06		489.06	489.06	489.06
Process Cost	$114,114.00	$108,108.00	$77,109.20	$55,059.20		$74,484.20	$98,984.20	$61,359.20
Process Scrap wgt. Ltns	171	171	171	171		0	0	0
Process Scrap cost	$84,268.80	$84,268.80	$84,268.80	$84,268.80		0	0	0
Rework, LHrs	978.12	480.48	480.48	480.48		0.00	0.00	0.00
Rework Cost	$34,234.20	$16,816.80	$16,816.80	$16,816.80		$0.00	$0.00	$0.00
Total Cost	$488,380.20	$464,956.80	$433,958.00	$411,908.00		$348,082.00	$372,582.00	$334,957.00
Material Cost:	$0.22	$0.22	$0.22	$0.22		$0.22	$0.22	$0.22
Labor Rate:	$35.00	$35.00	$35.00	$35.00		$35.00	$35.00	$35.00
Machine Duty Cycle:	1.00	1.00	0.80	0.80		0.80	0.80	0.80

costcmpx: Cost comparison at 85% machine utilization (ex. all "batch" at 100%)

	"Standard"	PAC						
	"Batch"	"Batch"	"Continuous"	"Continuous"		"Continuous"	"Continuous"	"Continuous"
	OFC		PAC	LC		SAW	GMAW	LW
Material	I-Beams	I-Beams	I-Beams	I-Beams		Plate strips	Plate strips	Plate strips
Mat'l Wgt, Ltns	690	690	690	690		476	476	476
Mat'l Cost	$340,032.00	$340,032.00	$340,032.00	$340,032.00		$234,572.80	$234,572.80	$234,572.80
Total # Tees	1716	1716	1716	1716		1716	1716	1716
Prep Time (Lhrs)	0	0	0	0		1115	1115	1115
Prep Labor Cost	$0.00	$0.00	$0.00	$0.00		$39,025.00	$39,025.00	$39,025.00
Prep Scrp (5%), LTns	0	0	0	0		23.8	23.8	23.8
Prep Scrap Cost	$0.00	$0.00	$0.00	$0.00		$11,728.64	$11,728.64	$11,728.64
Move to Process, LHrs	489.06	489.06	489.06	489.06		489.06	489.06	489.06
Process, Lhrs	2282.28	2110.68	1152.94	560.00		1082.35	1741.18	729.41
Move From Process, Lhrs	489.06	489.06	489.06	489.06		489.06	489.06	489.06
Process Cost	$114,114.00	$108,108.00	$74,587.14	$53,834.20		$72,116.55	$95,175.38	$59,763.61
Process Scrap wgt. Ltns	171	171	171	171		0	0	0
Process Scrap cost	$84,268.80	$84,268.80	$84,268.80	$84,268.80		0	0	0
Rework, LHrs	978.12	480.48	480.48	480.48		0.00	0.00	0.00
Rework Cost	$34,234.20	$16,816.80	$16,816.80	$16,816.80		$0.00	$0.00	$0.00
Total Cost	$488,380.20	$464,956.80	$431,435.94	$410,683.00		$345,714.35	$368,773.18	$333,361.41
Material Cost:	$0.22	$0.22	$0.22	$0.22		$0.22	$0.22	$0.22
Labor Rate:	$35.00	$35.00	$35.00	$35.00		$35.00	$35.00	$35.00
Machine Duty Cycle:	1.00	1.00	0.85	0.85		0.85	0.85	0.85

costcmpy: Cost comparison at 90% machine utilization (ex. all "batch" at 100%)

	"Standard" "Batch" OFC	PAC "Batch"	"Continuous" PAC	"Continuous" LC		"Continuous" SAW	"Continuous" GMAW	"Continuous" LW
Material	I-Beams	I-Beams	I-Beams	I-Beams		Plate strips	Plate strips	Plate strips
Mat'l Wgt, Ltns	690	690	690	690		476	476	476
Mat'l Cost	$340,032.00	$340,032.00	$340,032.00	$340,032.00		$234,572.80	$234,572.80	$234,572.80
Total # Tees	1716	1716	1716	1716		1716	1716	1716
Prep Time (Lhrs)	0	0	0	0		1115	1115	1115
Prep Labor Cost	$0.00	$0.00	$0.00	$0.00		$39,025.00	$39,025.00	$39,025.00
Prep Scrp (5%), LTns	0	0	0	0		23.8	23.8	23.8
Prep Scrap Cost	$0.00	$0.00	$0.00	$0.00		$11,728.64	$11,728.64	$11,728.64
Move to Process, LHrs	489.06	489.06	489.06	489.06		489.06	489.06	489.06
Process, Lhrs	2282.28	2110.68	1088.89	528.89		1022.22	1644.44	688.89
Move From Process, Lhrs	489.06	489.06	489.06	489.06		489.06	489.06	489.06
Process Cost	$114,114.00	$108,108.00	$72,345.31	$52,745.31		$70,011.98	$91,789.76	$58,345.31
Process Scrap wgt. Ltns	171	171	171	171		0	0	0
Process Scrap cost	$84,268.80	$84,268.80	$84,268.80	$84,268.80		0	0	0
Rework, LHrs	978.12	480.48	480.48	480.48		0.00	0.00	0.00
Rework Cost	$34,234.20	$16,816.80	$16,816.80	$16,816.80		$0.00	$0.00	$0.00
Total Cost	$488,380.20	$464,956.80	$429,194.11	$409,594.11		$343,609.78	$365,387.56	$331,943.11
Material Cost:	$0.22	$0.22	$0.22	$0.22		$0.22	$0.22	$0.22
Labor Rate:	$35.00	$35.00	$35.00	$35.00		$35.00	$35.00	$35.00
Machine Duty Cycle:	1.00	1.00	0.90	0.90		0.90	0.90	0.90

costcmpz: Cost comparison at 95% machine utilization (ex. all "batch" at 100%)

	"Standard" "Batch" OFC	PAC "Batch"	"Continuous" PAC	"Continuous" LC		"Continuous" SAW	"Continuous" GMAW	"Continuous" LW
Material	I-Beams	I-Beams	I-Beams	I-Beams		Plate strips	Plate strips	Plate strips
Mat'l Wgt, Ltns	690	690	690	690		476	476	476
Mat'l Cost	$340,032.00	$340,032.00	$340,032.00	$340,032.00		$234,572.80	$234,572.80	$234,572.80
Total # Tees	1716	1716	1716	1716		1716	1716	1716
Prep Time (Lhrs)	0	0	0	0		1115	1115	1115
Prep Labor Cost	$0.00	$0.00	$0.00	$0.00		************	$39,025.00	$39,025.00
Prep Scrp (5%), LTns	0	0	0	0		23.8	23.8	23.8
Prep Scrap Cost	$0.00	$0.00	$0.00	$0.00		$11,728.64	$11,728.64	$11,728.64
Move to Process, LHrs	489.06	489.06	489.06	489.06		489.06	489.06	489.06
Process, Lhrs	2282.28	2110.68	1031.58	501.05		968.42	1557.89	652.63
Move From Process, Lhrs	489.06	489.06	489.06	489.06		489.06	489.06	489.06
Process Cost	$114,114.00	$108,108.00	$70,339.46	$51,771.04		$68,128.94	$88,760.52	$57,076.31
Process Scrap wgt. Ltns	171	171	171	171		0	0	0
Process Scrap cost	$84,268.80	$84,268.80	$84,268.80	$84,268.80		0	0	0
Rework, LHrs	978.12	480.48	480.48	480.48		0.00	0.00	0.00
Rework Cost	$34,234.20	$16,816.80	$16,816.80	$16,816.80		$0.00	$0.00	$0.00
Total Cost	$488,380.20	$464,956.80	$427,188.26	$408,619.84		$341,726.74	$362,358.32	$330,674.11
Material Cost:	$0.22	$0.22	$0.22	$0.22		$0.22	$0.22	$0.22
Labor Rate:	$35.00	$35.00	$35.00	$35.00		$35.00	$35.00	$35.00
Machine Duty Cycle:	1.00	1.00	0.95	0.95		0.95	0.95	0.95

TEE BEAM MANUFACTURING ANALYSIS

FOR

WEIGHT REDUCTION AND PRODUCIBILITY

NSRP PROJECT #N7-91-4

APPENDIX C

TO

FINAL REPORT

MOCK-UP TESTING

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October 31, 1994

Contents/List of Illustrations

I Summary

Large and small scale mockup tests were performed using a number of traditional and newer methods of cutting and welding. Brief descriptions and representative photographs of the results are included herein. In all but one case, testing was done at no charge, in the interest of exploring new applications for these technologies.

One important consideration must be applied to this series of tests: available equipment was not necessarily configured to provide optimum performance on the test pieces. Furthermore, time and finding constraints as well as the nature of this survey did not allow for thorough parameter optimization or any kind of hardware development. This can have a significant affect on the quality of cut surfaces, or the speed of cutting or welding, and therefore the distortion induced in the test piece. Poor results do not necessarily mean that a given method cannot perform the function well. Development of task-specific tooling may in fact make the methodology competitive in both speed and quality. The fact remains, however, that these results represent the current state of the art, and that further development of hardware and procedures is necessary if these methods are to compete with traditional low-cost oxy-fuel cutting systems.

Methods used for mock-up testing were: abrasive water jet cutting (AWJC); laser beam cutting (LBC); plasma-arc cutting (PAC); oxyfuel cutting (OFC); laser beam welding (LBW).

Where available equipment was not configured to allow simultaneous parallel stripping cuts, or to make simultaneous dual tee-section welds, the stripping or welding test was done in two sequential operations. While this provided some degree of judgment about how the process might perform if adapted to the task of producing tee shapes, the effect of two simultaneous cuts or welds on distortion could not be fully explored.

To provide a standard section for cutting tests, 6x20# wide-flange I-beams, in the mid-range of weight and thickness of the target group, were used. These were cut into sections of the maximum length possible for processing at the given facility. In general, test pieces were only two feet long, but a few eight-foot pieces were cut. Short pieces could only establish parameters for a given speed and cut-surface quality; eight-foot and longer mockups were necessary to evaluate distortion. Forty-foot lengths could only be produced by OFC and PAC.

Since the traditional welding processes are well understood, only one welding test was performed, using C02 laser welding. The 6x20# shape was approximated by using 3/8x6 inch flat bars for both web and flange. Included for information in Section VII are data and photographs of a machine used at Bath Iron Works for submerged arc welding on forty-nine foot long HSLA-80 tee shapes. This device produced more than twenty-one miles of tee section with negligible distortion.

The following small-scale mock-up cutting tests were performed:

- Laser cutting of two-foot sections at Applied Research Laboratory, PennState University, using 2.4kW Hobart YAG and 1.5 kW C02 lasers.
- Laser cutting of eight-foot sections at ARL using the 14 kW UTIL C02 laser.
- Laser cutting of two-foot sections using the 3 kW GE Fanuc C02 laser at Edison Welding Institute.
- Laser cutting of two-foot sections using a 3 kW YAG laser at Hobart Laser Products.
- Abrasive water jet cutting of an eight-foot section at Laser Applications Inc.
- Oxy-fuel cutting of eight-foot sections at Bath Iron Works

The following large-scale mock-up cutting tests were performed:

- Oxyfuel cutting of forty-foot sections at Bath Iron Works
- Plasma-arc cutting of forty-foot sections at Bath Iron Works

The following large scale welding test was performed:

- Laser welding of twenty-foot sections using the 25 kW C02 laser at Stardyne, Inc.

Summary of Mock-up Tests

- Laser and plasma processes cut at higher travel speeds than the oxyfuel process, while cut edge quality was nearly as good as that produced by traditional burning.
- In general, the processes tested performed at lower speeds than originally estimated. Typically, this was due to the radius at the flange to web transition.
- Abrasive water jet cutting produced no measurable distortion, but eight-foot sections were really too short to provide significant distortion with any process.
- Plasma cutting of forty-foot sections resulted in approximately half as much distortion as that produced by oxyfuel cutting.
- Water sprayed on the parts being cut will reduce distortion by nearly 50%.
- Autogenous laser welds in twenty-foot parts produced little distortion, but when filler metal was added to provide fillet reinforcement, distortion increased.

Distortion measurements taken are summarized below: It is unfortunate that more data could not be generated in this program, especially for long sections cut by other processes. The use of eight-foot sections did not provide enough length to gain much insight into potential distortion which might be produced by laser cutting. Indeed, the oxyfuel result for eight foot parts is contradictory, but the numbers are so small that it is difficult to draw a conclusion.

Water spray is one of the simplest and most useful methods for reducing distortion. In these tests, a trickling stream from a small nozzle positioned immediately behind the cutting head reduced camber by more than 50% for both the plasma and oxyfuel processes.

Table I. Distortion Measurements

Process	Measured Camber (inches)				
	8' Dry	8' Water	40' Dry	40' Water	20' Welded
Abrasive Water Jet, single cuts		0			
14 kW CO2 Laser, single cuts	1/16				
Oxyfuel, single cuts	1/32	1/16			
Oxyfuel, double cuts	1/8	1/8	4-21/32	2-3/16	
Plasma, double cuts			2-3/4	1-3/16	
Laser weld, autogenous					5/32

II Abrasive Water Jet Cutting at Laser Applications, Inc., Westminster MD

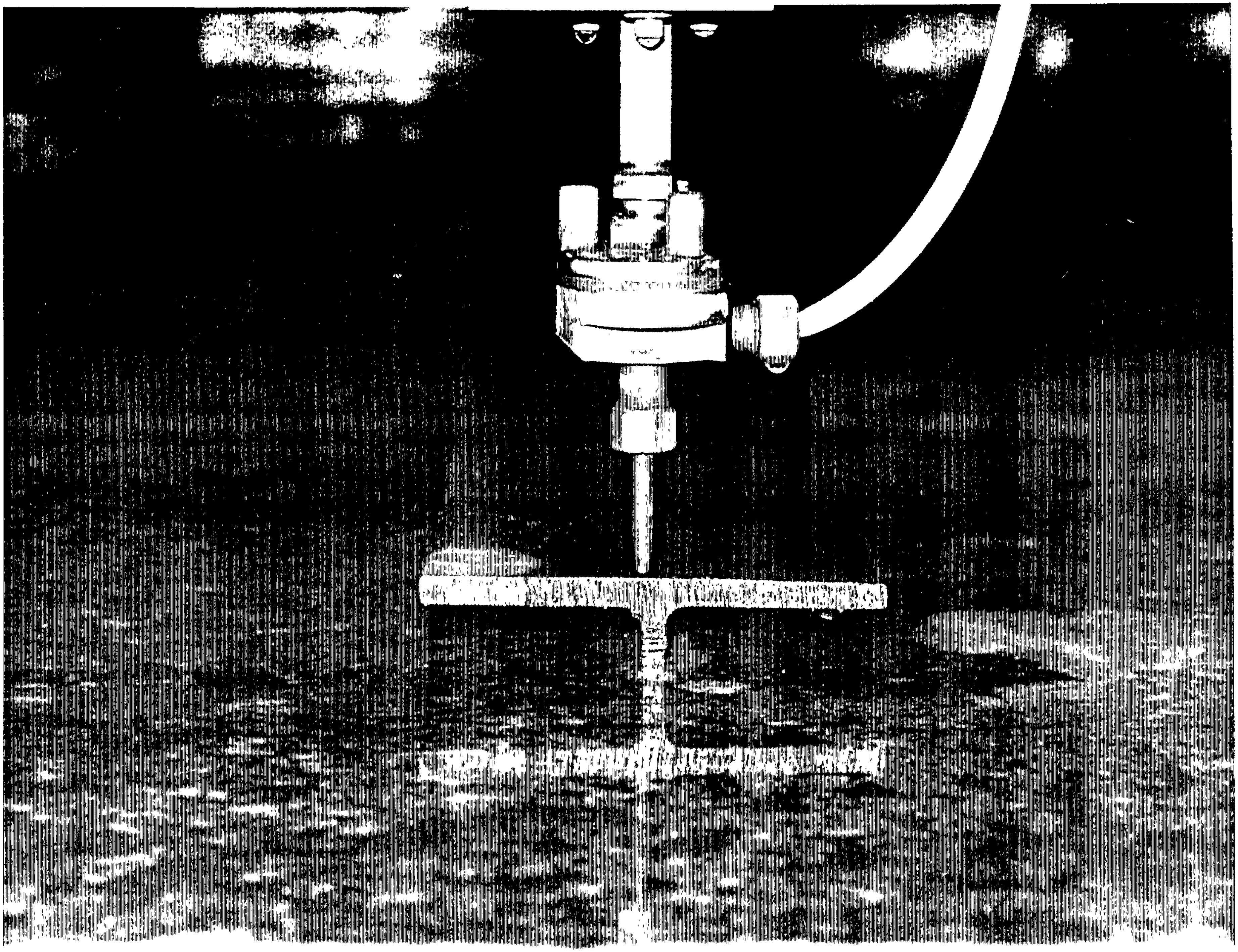
Since thermally induced distortion is a major cause of rework in stripping by means of Oxy-Fuel Cutting (OFC), a comparison was sought with a method which used no heat. LAI had offered to perform test cuts on an eight-foot section of 6x6x20# I-Beam at no charge.

The I-Beam was stripped under a six-axis Cimcorp robotic gantry workcell which had a 16-foot square work area. Cutting was done under water, in a stationary tank equipped with a ballasting system for raising and lowering the water level. The cutting system had a single nozzle, so two separate passes were required to complete the stripping operation. Operating at 50,000 psi, the water jet used garnet abrasive which was aspirated into the flow stream near the output nozzle (Fig. 1). Approximately 50 lbs of garnet were consumed during this test. Since half of the crystals fracture in the stream prior to reaching the cut, and the other half are consumed in the cutting process itself the garnet is not recyclable: indeed, particles of the material being cut contaminate any residual abrasive material. This system is capable of cutting most materials up to 6 inches in thickness; in general, the water pressure is constant, and travel speed is slowed for thicker material. Kerf widths observed were less that 1/16-inch, with a barely noticeable beveling of the cut face, symmetrically disposed on either side of the kerf. The system can be programmed to correct this bevel angle by angling the 6-axis head.

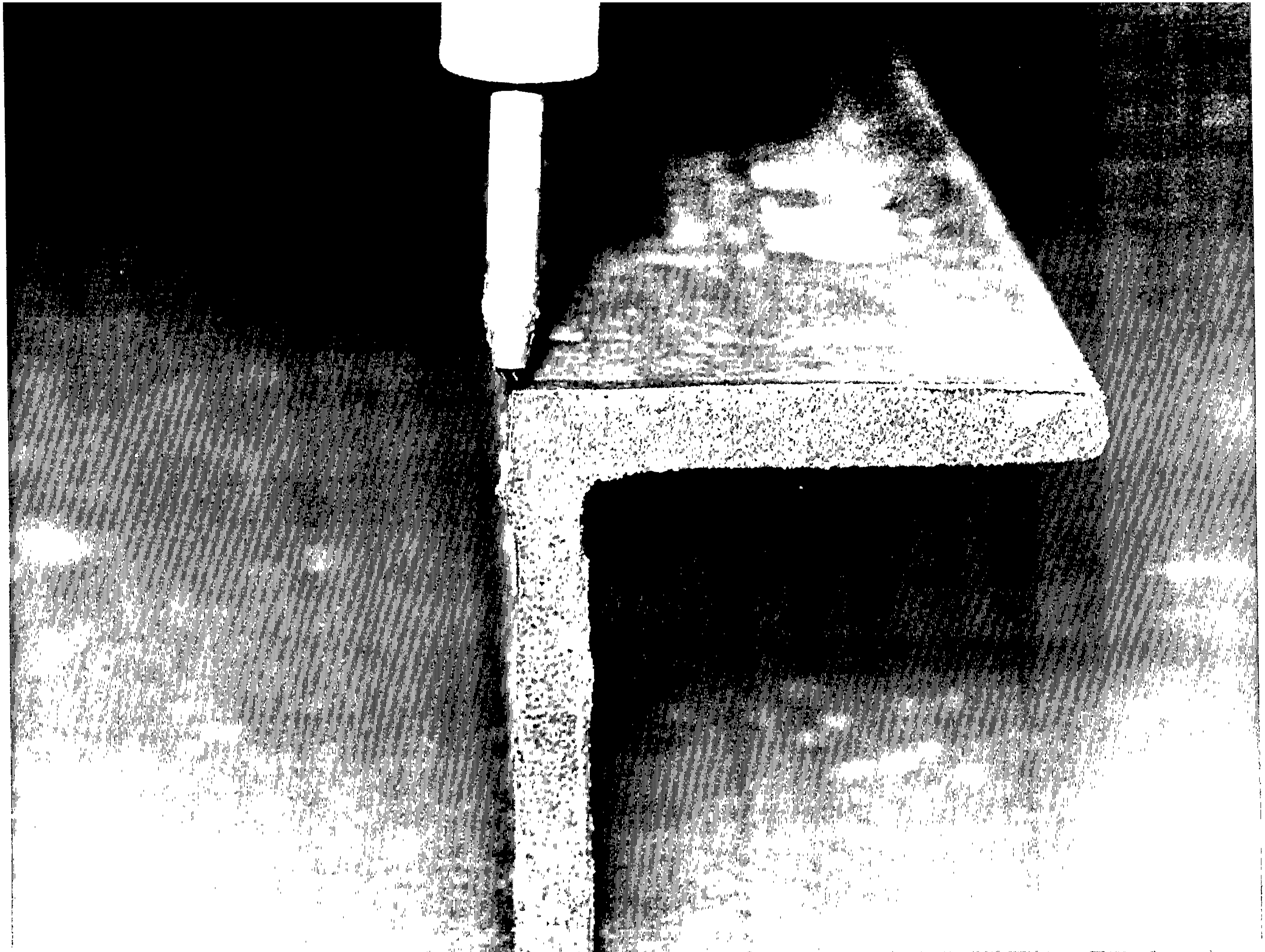
Test cuts were made on a scrap piece of 10-inch I-beam with flanges 7/8-inch in thickness. Travel speeds for these tests ran in the range of 3-5 inches per minute. The actual cutting on the 6x6-inch section was done with travel speeds ranging from 3.5 to 6 inches per minute, since the 3/8-inch flanges did not have as great a cut face. The initial cut was setup with a 2-degree offsetting angle (Fig.2), since it was felt that the water stream might damage the web of the beam, or the lower flange if the cut was made exactly normal to the flange. This cut was run initially at 6 ipm, but complete penetration was not achieved, requiring a reduction to 5 ipm, which proved successful. The second cut was deliberately made with the nozzle normal to the flange, so that the effect of the exit stream on the web and lower flange could be discovered. The cut face was substantially wider (almost one inch, as in Fig. 3), due to the radius at the root of the flange, and travel speed had to be reduced to 3.5 ipm to successfully make this cut.

In general, the cut quality was excellent, with a slight appearance of drag lines in the regions where travel speed was initially set too high; drag lines were also noticeable in the thicker cut faces, although the profile was very shallow, compared to OFC. While the process produces no oxide films or remelted zones on the cut face, the surfaces begin to show a light rusting, (the water in the tank has no corrosion inhibitors) in less than one-half hour. There was no damage to the web of the bar, or the lower flange. The only noticeable effect was the removal of mill scale and rust form the web and radius area of the lower flange.

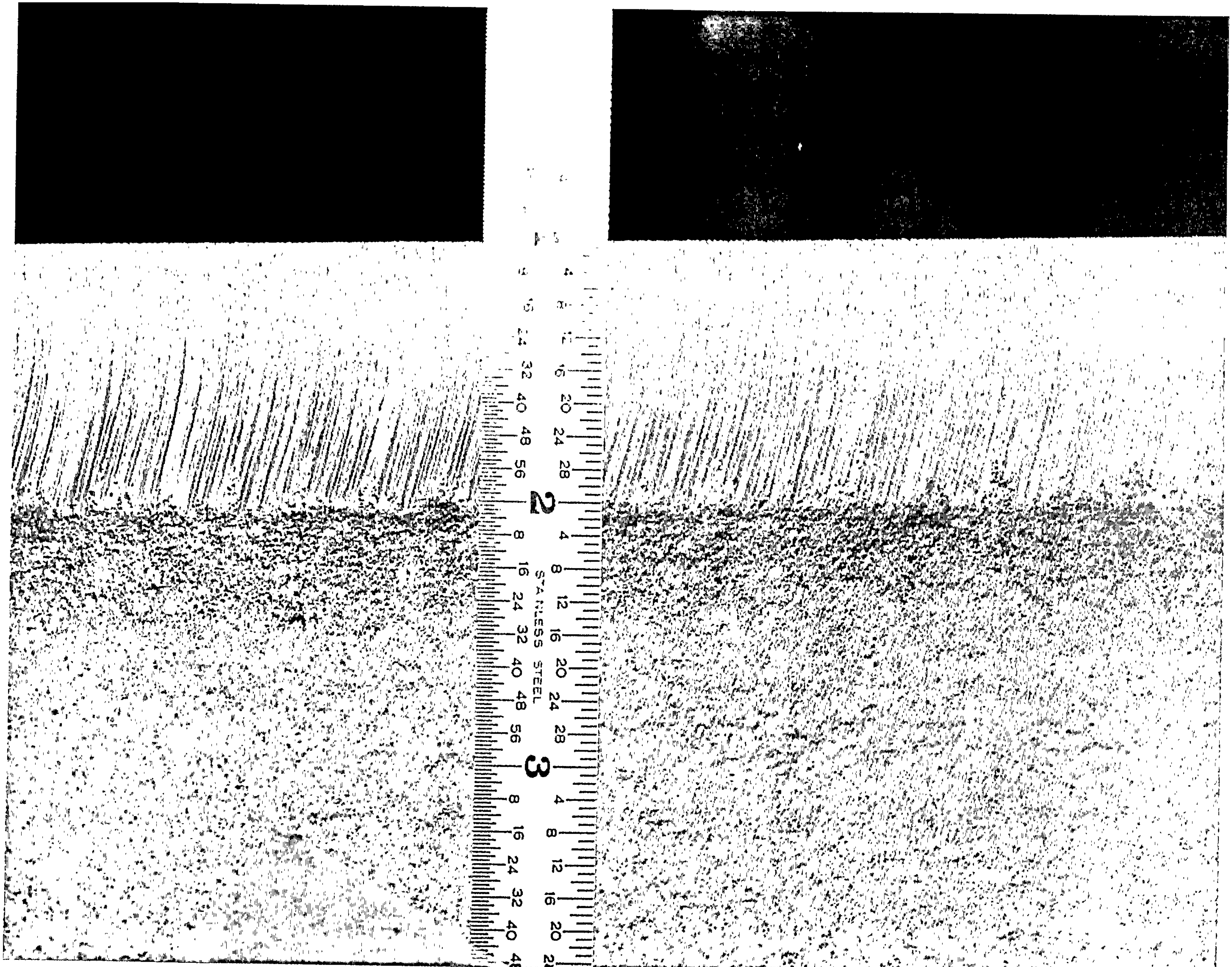
Distortion was not noticeable: the original beam was reasonably true, with little camber, sweep or twist, and final measurements of the tee showed no measurable change. This tends also to indicate that the as-received I-beam does not have significant residual stresses, which would cause distortion when unbalanced by removal of only one pair of flanges. The flange material did show a very slight bowing: when laid on a flat table with ends held tightly together, there was an open space of about 3/32 inch in the middle, indicating approximately 3/64 inch of bow per flange strip.



1. Alignment of nozzle to flange, W6x20 beam, abrasive Water jet cutting unit at Laser Applications, Inc.



2. I-beam after removal of one flange



3. Surface appearance and width of abrasive water jet cut (note that flange has been removed flush with web surface)

III Laser Cutting

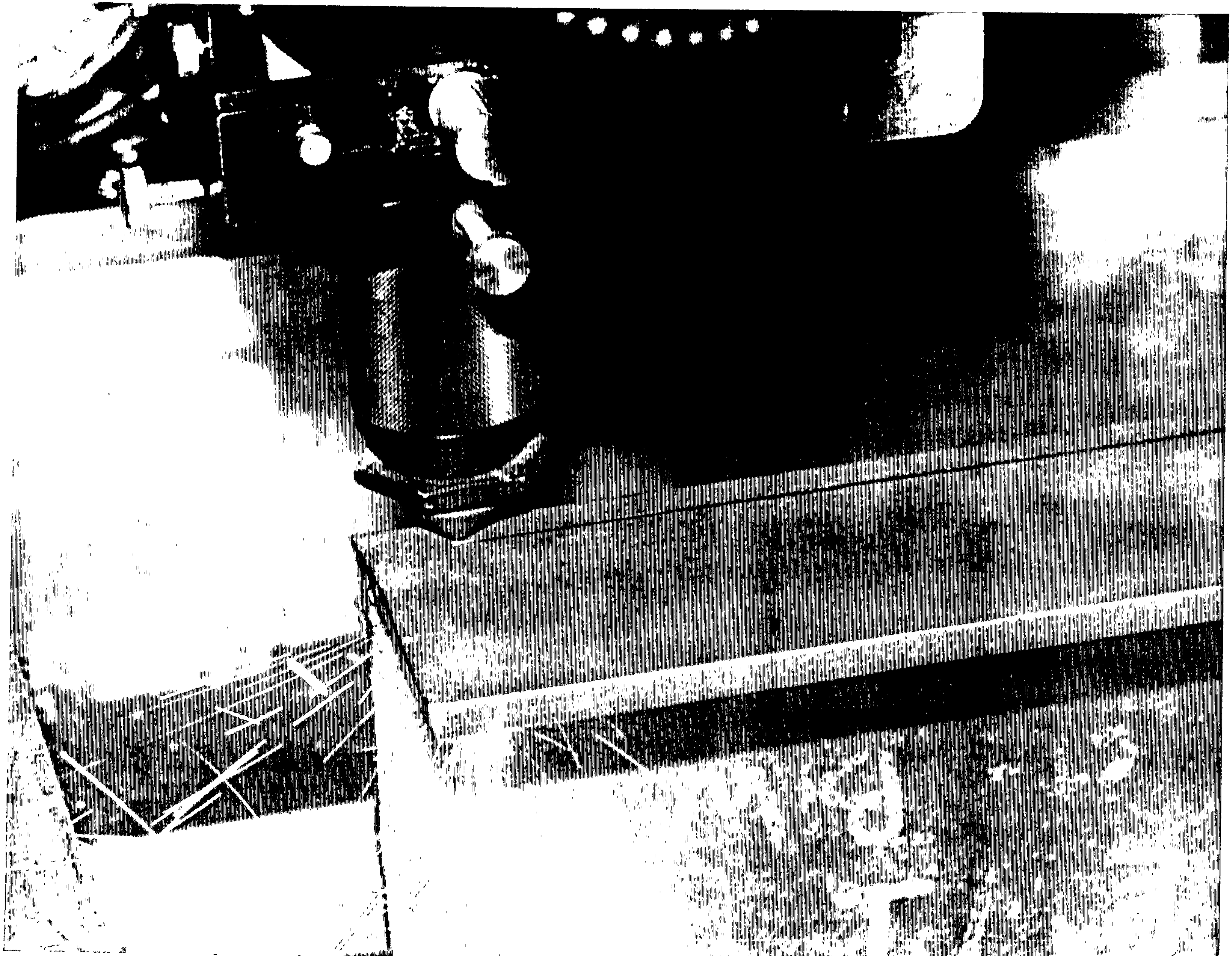
Cutting of two-foot mockup pieces was done at Edison Welding Institute, using a 3 kW GE Fanuc C02 laser equipped with a 5-inch focal length lens. Cutting was performed at a l-inch standoff, and 38 ipm travel speed. Oxygen at 20 psi was used to assist cutting, which was done with the laser working at the full 3 kW rating. Fig. 4 shows the cut in progress, and gives an idea of the narrow kerf possible with laser cutting. Figure 5 shows the resultant cut before any slag has been removed. Cut quality was good to excellent as shown in Figure 6. Both primed and rusty flange material were cut, and no difference in performance was noted. For the first pass, the cut was positioned to leave approximately .O1-inch of flange stub protruding from the web, and the second pass was run with the cut surface slightly into the web. This did not cause damage to the web below the cut, in fact, the cut broke outward through the radius transition area. This is not readily evident in Figure 6, since the cut was virtually flush with the flange. If a cut had been made this close to the web with the OFC process, a significantly deep gouge extending down the web would have resulted.

A 3 kW YAG laser was demonstrated at Hobart Laser Products. Cutting was typically done at 2.4 kW power, with Oxygen at 32 psi to assist. Focal length of the lens was four inches, typical for this kind of application. Figure 7 shows the laser deflanging an 8x10# I-beam, which was used to develop some baseline parameters prior to cutting the 6x20# I-beam test piece. Figure 8 shows the cut surface quality. Figure 9 shows the cut surface of the 6x20# mockup specimen. As noted in these two pictures, the travel speed was reduced from 40 ipm to 32 ipm to handle the thicker flanges of the 6x20# beam.

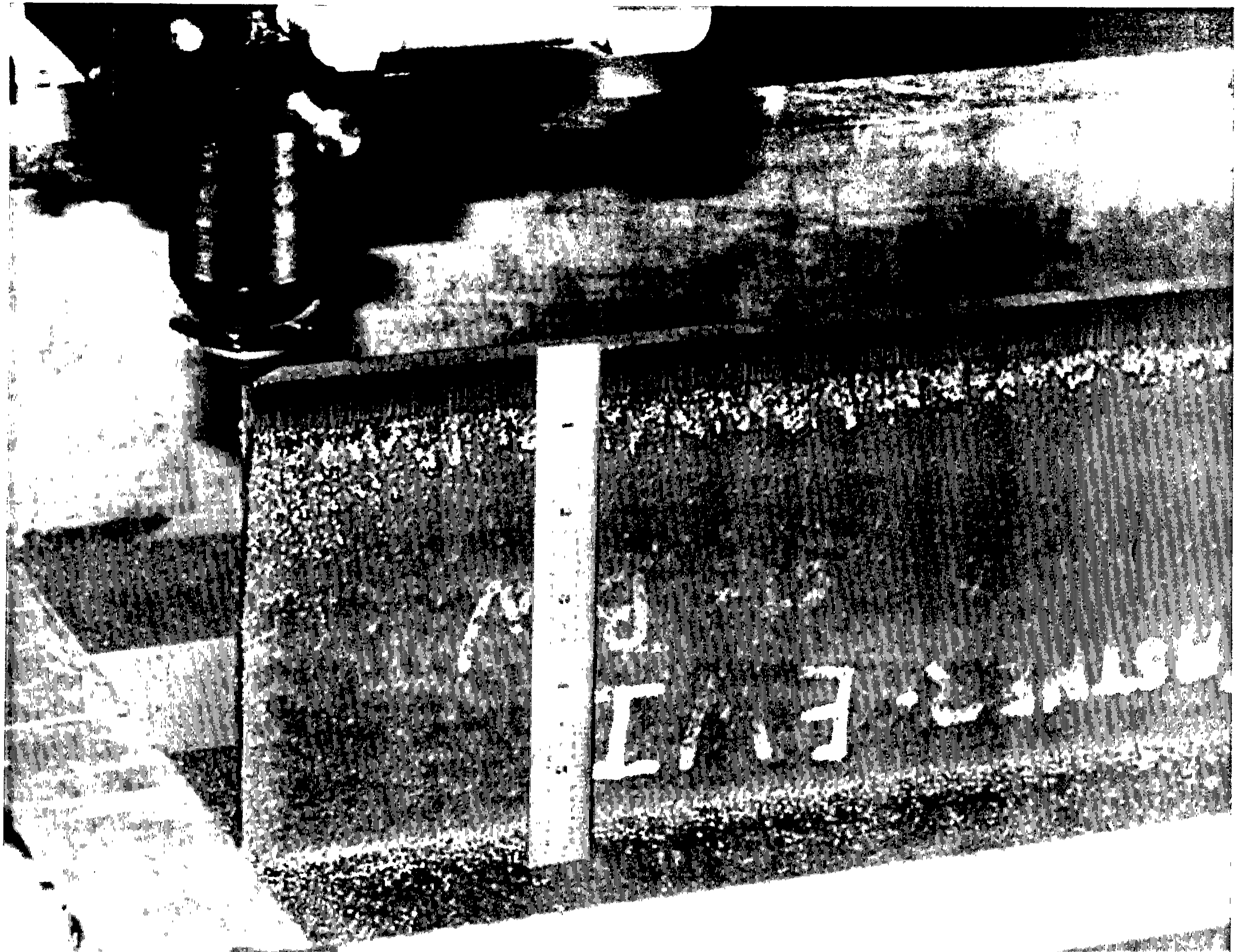
Eight-foot long pieces of 6x20# beam were cut at the Applied Research Laboratory at Pennsylvania State University using the 14 kW UTIL C02 laser and the LARS (Laser Articulating Robot System). This system was adapted for cutting by adding a gas nozzle which blew oxygen on the flanges at the focus point. Oxygen was used at pressures of 140 psi, and flow rates up to 150 cfh. Other gases such as Nitrogen and air were used, but Oxygen was necessary for consistently good cut quality. The system cut surprisingly well, in spite of the fact that most C02 lasers configured for cutting use a nozzle designed to allow gas flow to be nearly concentric with the beam. Several travel speeds were evaluated, with 40 ipm observed as a practical maximum for this equipment. Figure 10 shows both cut and uncut beams. Figures 11 and 12 are representative of the cut-edge quality achieved with this system.

Other laser devices were tested. Cutting was also done on two-foot sections of 6x20# beam, using 1.8 kW Hobart YAG and 1.5 kW C02 lasers at Applied Research Laboratory. Other tests were made at Coherent General, Sturbridge, Massachusetts, using a 3-kW C02 laser, again cutting two-foot long sections of 6x20# beam. Results were generally typical of those listed above, except that the 1.8 kW YAG unit required much lower travel speeds to cut all the way through.

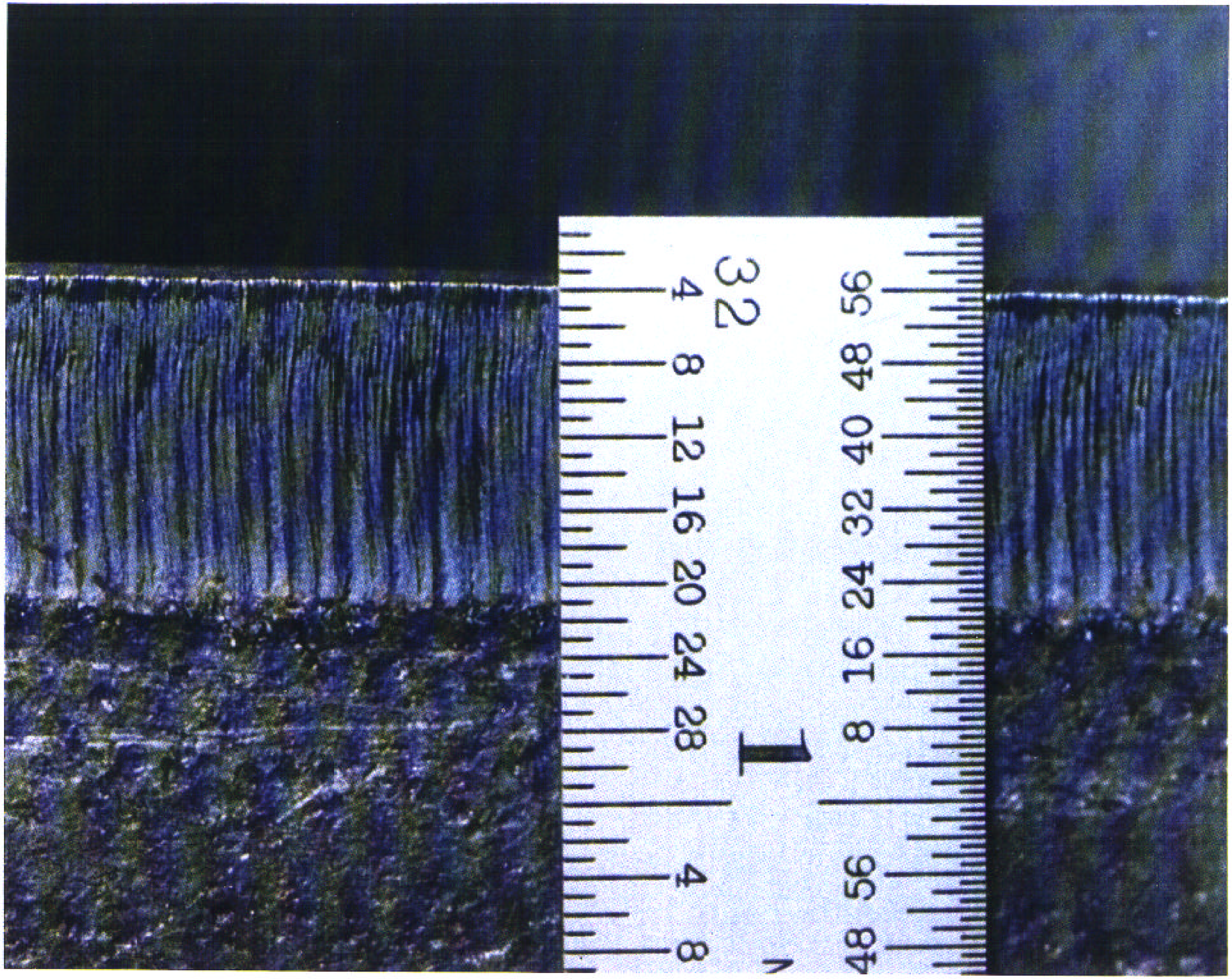
While it is evident from Table I that conclusions about thermally induced distortion cannot be categorically drawn from the 8-foot long sections, the general body of experience with laser cutting is that distortion is lower than that experienced with OFC. Significant testing with longer pieces is necessary to establish that this is true for deflanging of I-beams.



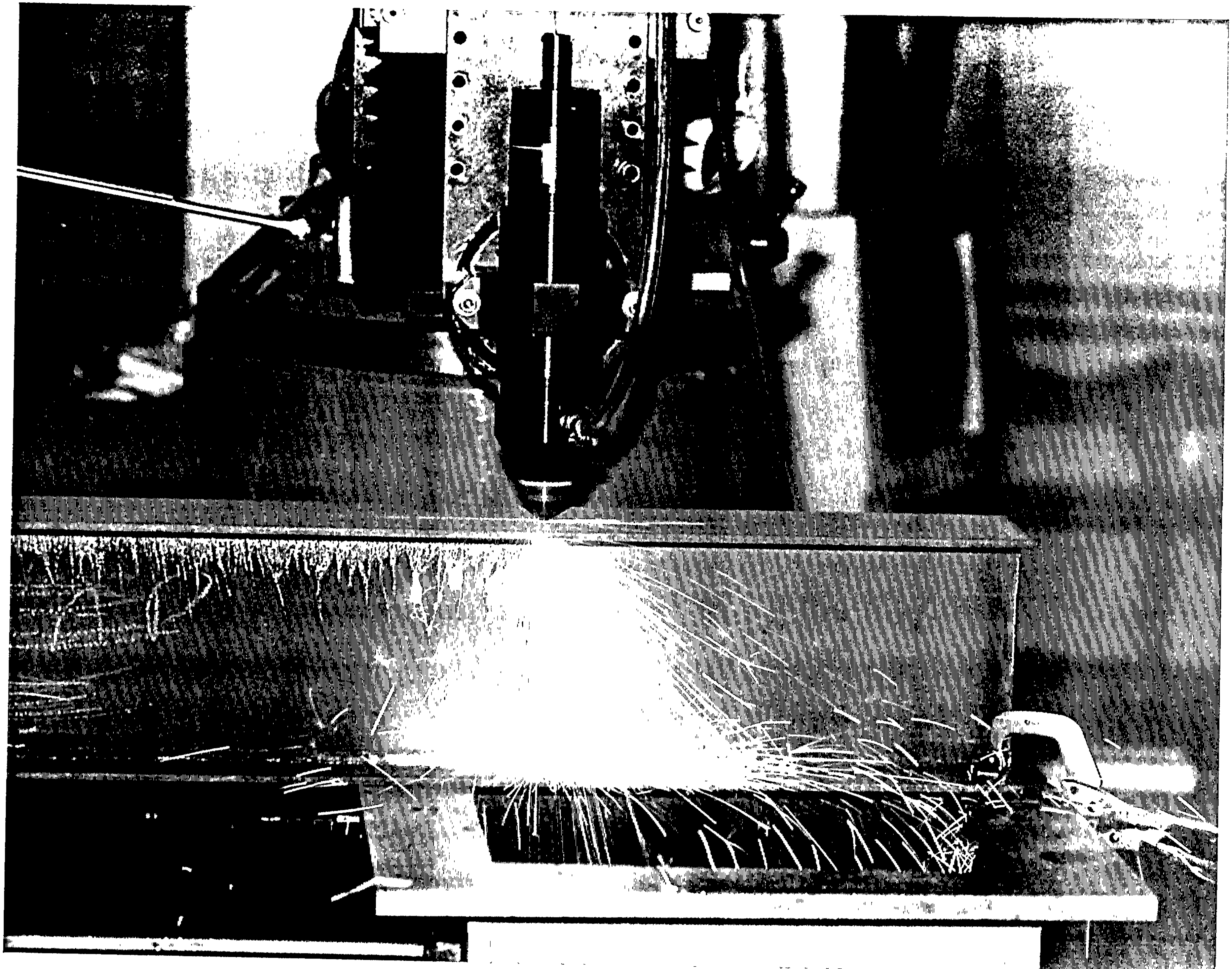
4. 3-kW CO2 laser at EWI, second flange cut on W6x20 beam



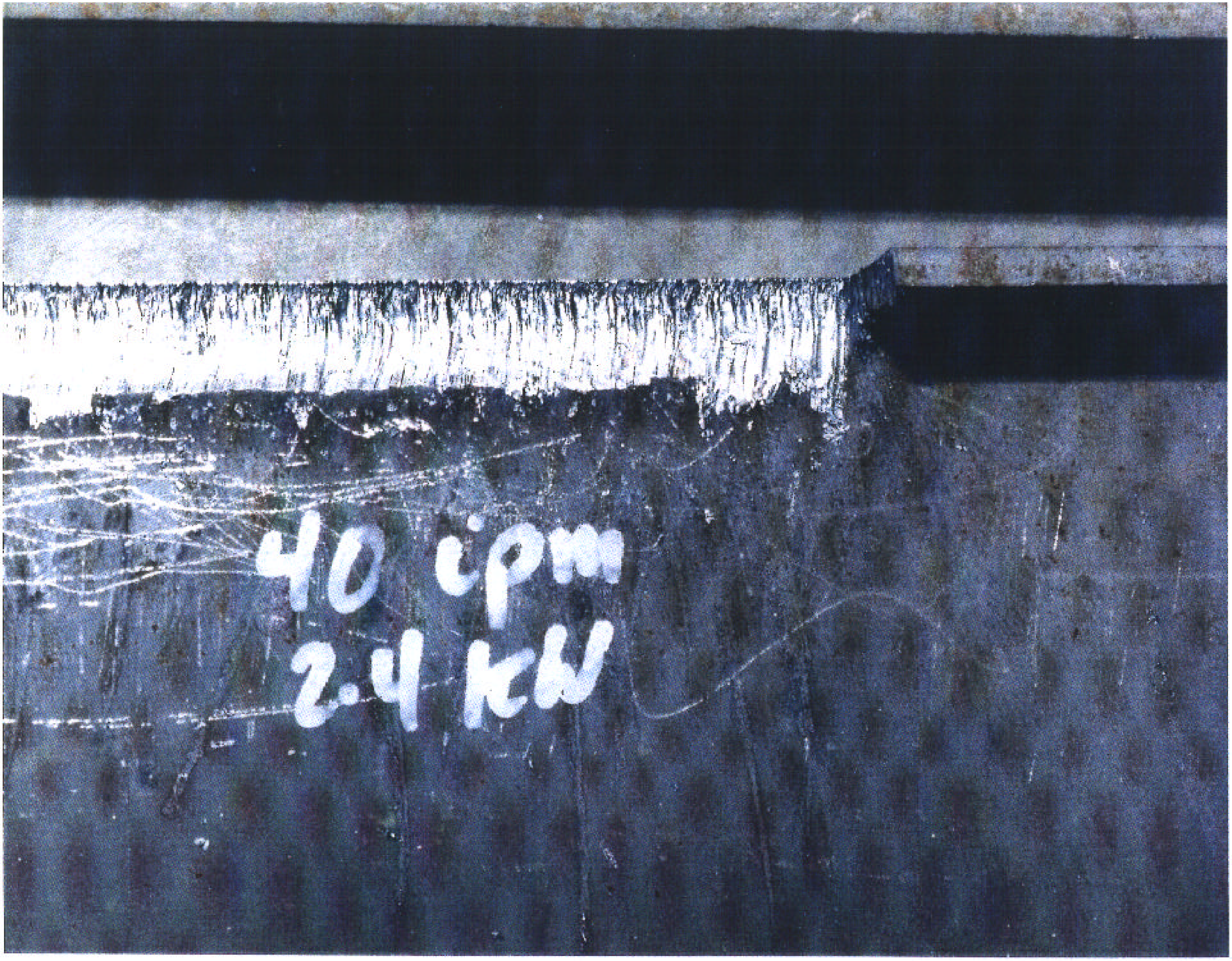
5. As-cut surface appearance, 3-kW CO2 laser, W6x20 beam



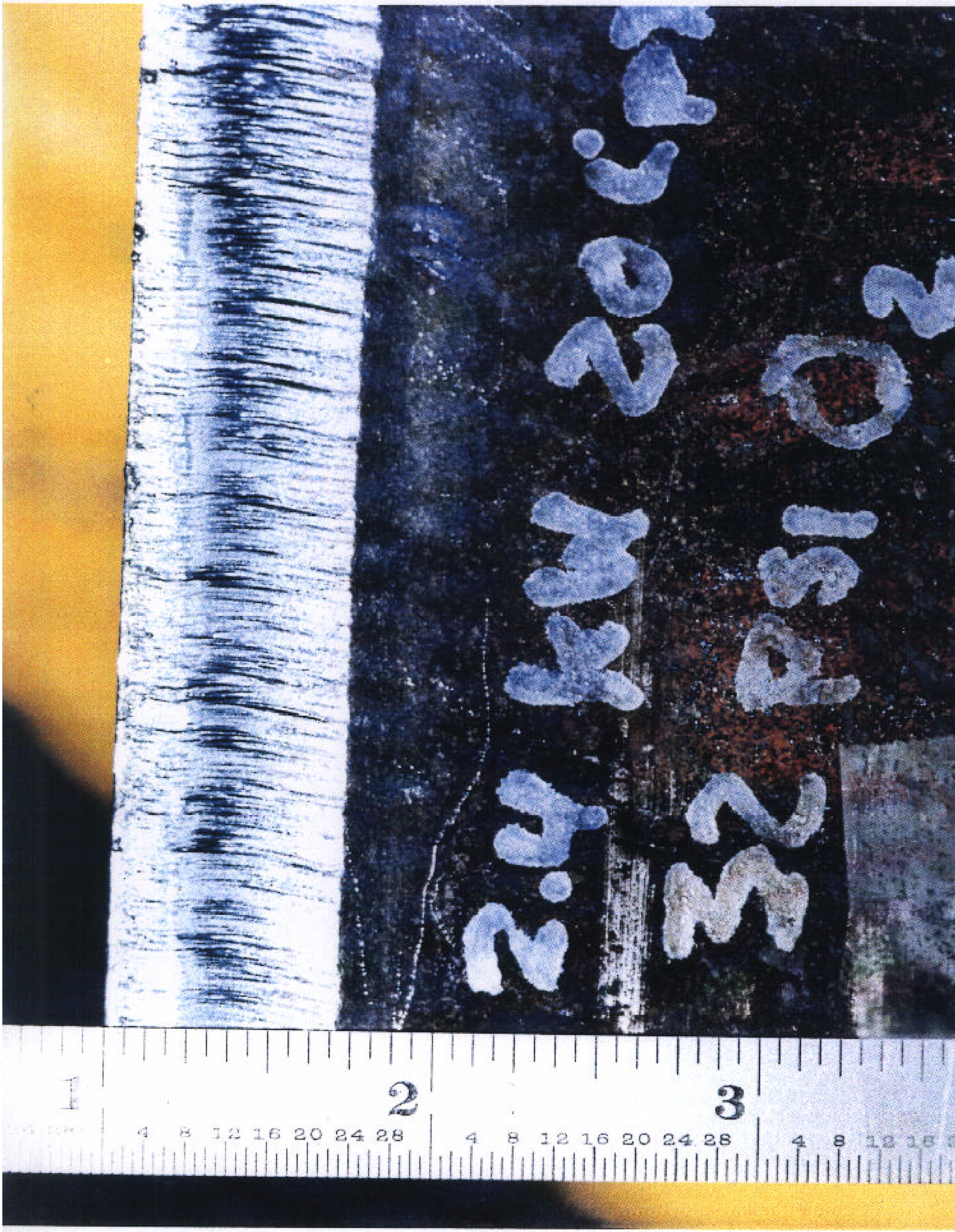
6. Cut surface appearance and width, 3-kW CO2 Laser, W6x20 beam



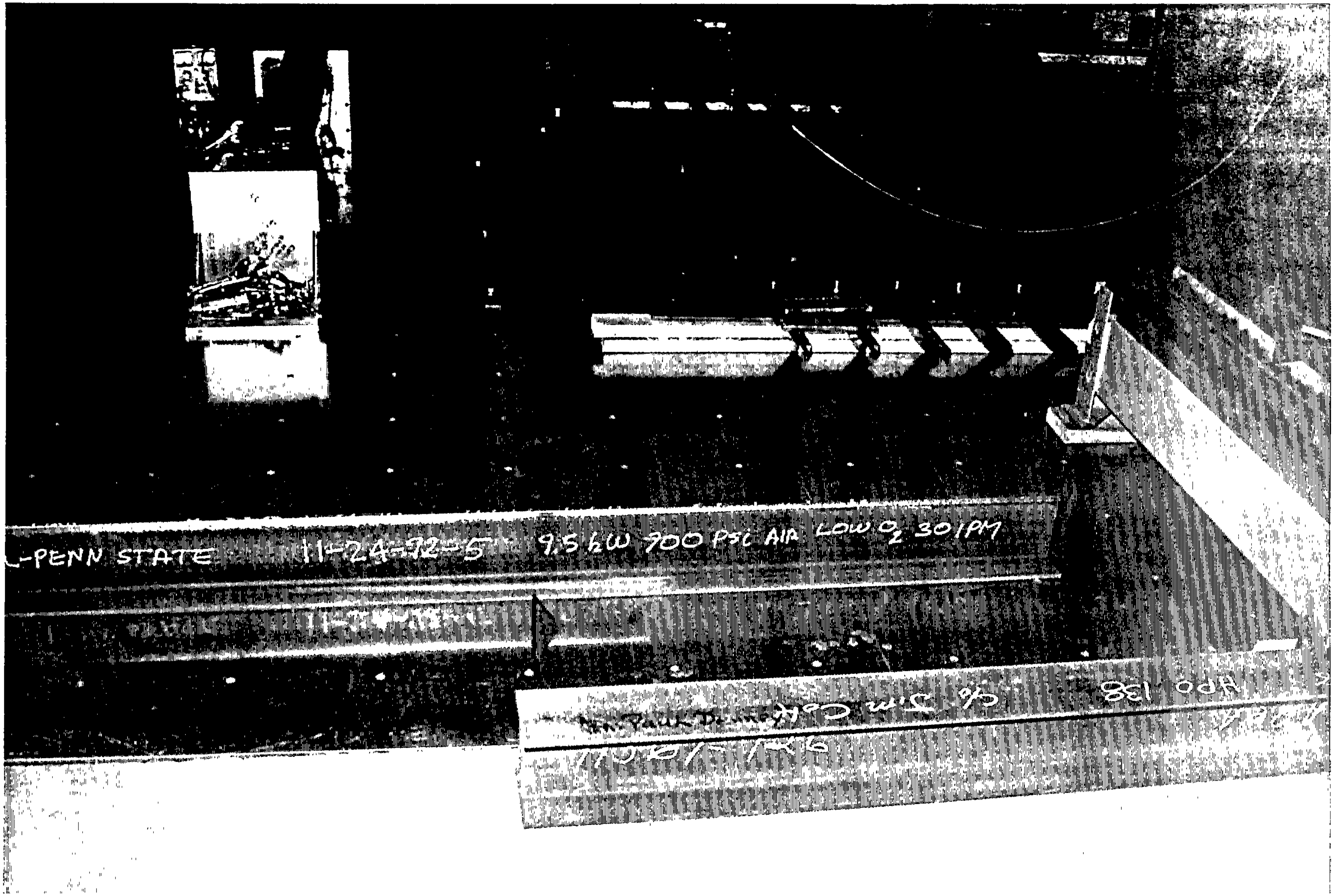
7. 3 kW YAG Laser at Hobart, first flange cut on W8x10 beam



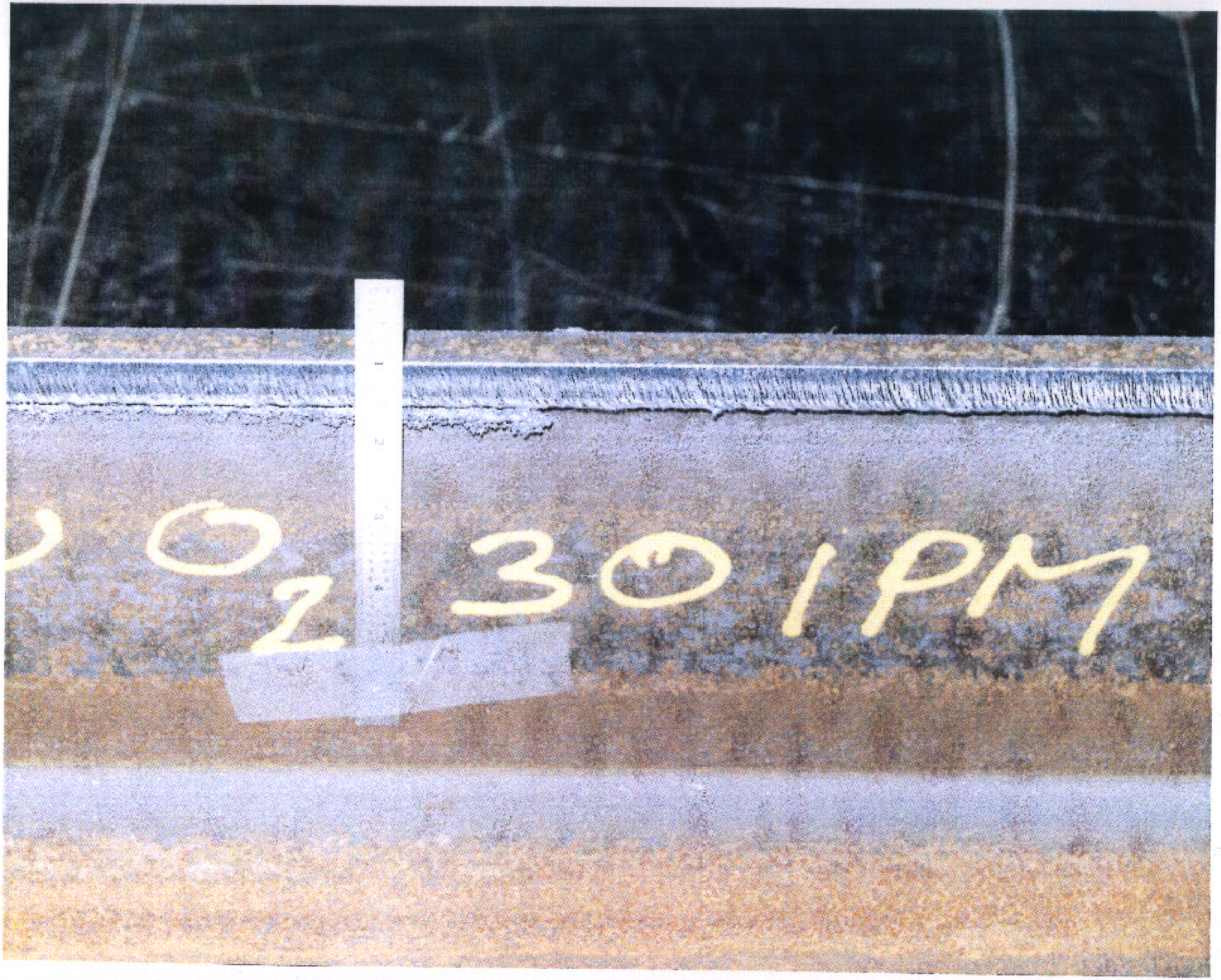
8. Cut surface appearance, 3kW YAG laser, W8x10 beam



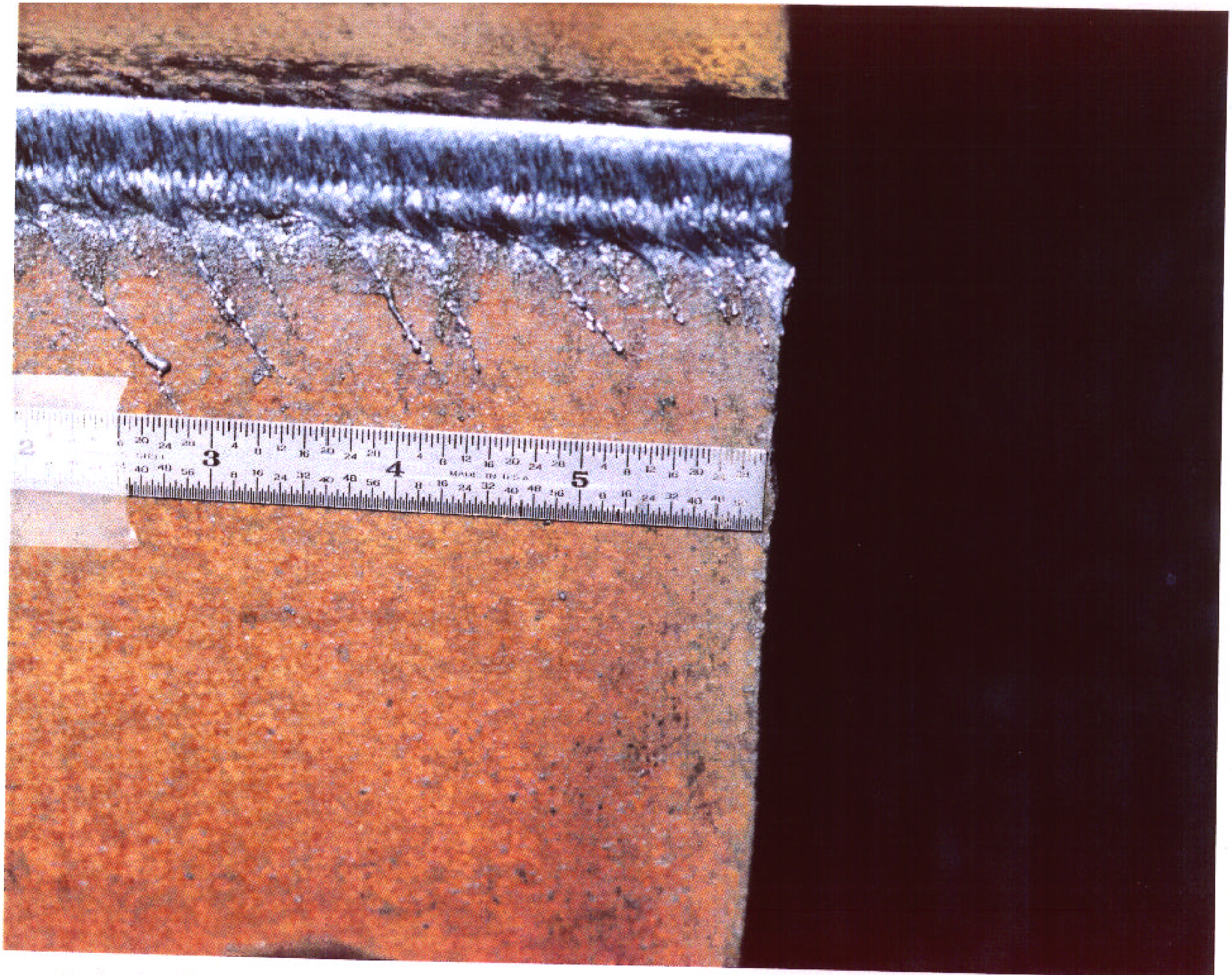
9. Cut surface appearance and width, 3kW YAG on W6x20 beam



10. 14 kW CO2 laser at ARL, appearance of cut vs. uncut W6x20 beams



11. As-cut surface appearance and width, 14 kW CO2 laser at ARL. W6x20 beam



12. As-cut surface appearance, 14 kW CO_2 laser, W6x20 beam, prior to removal of slag

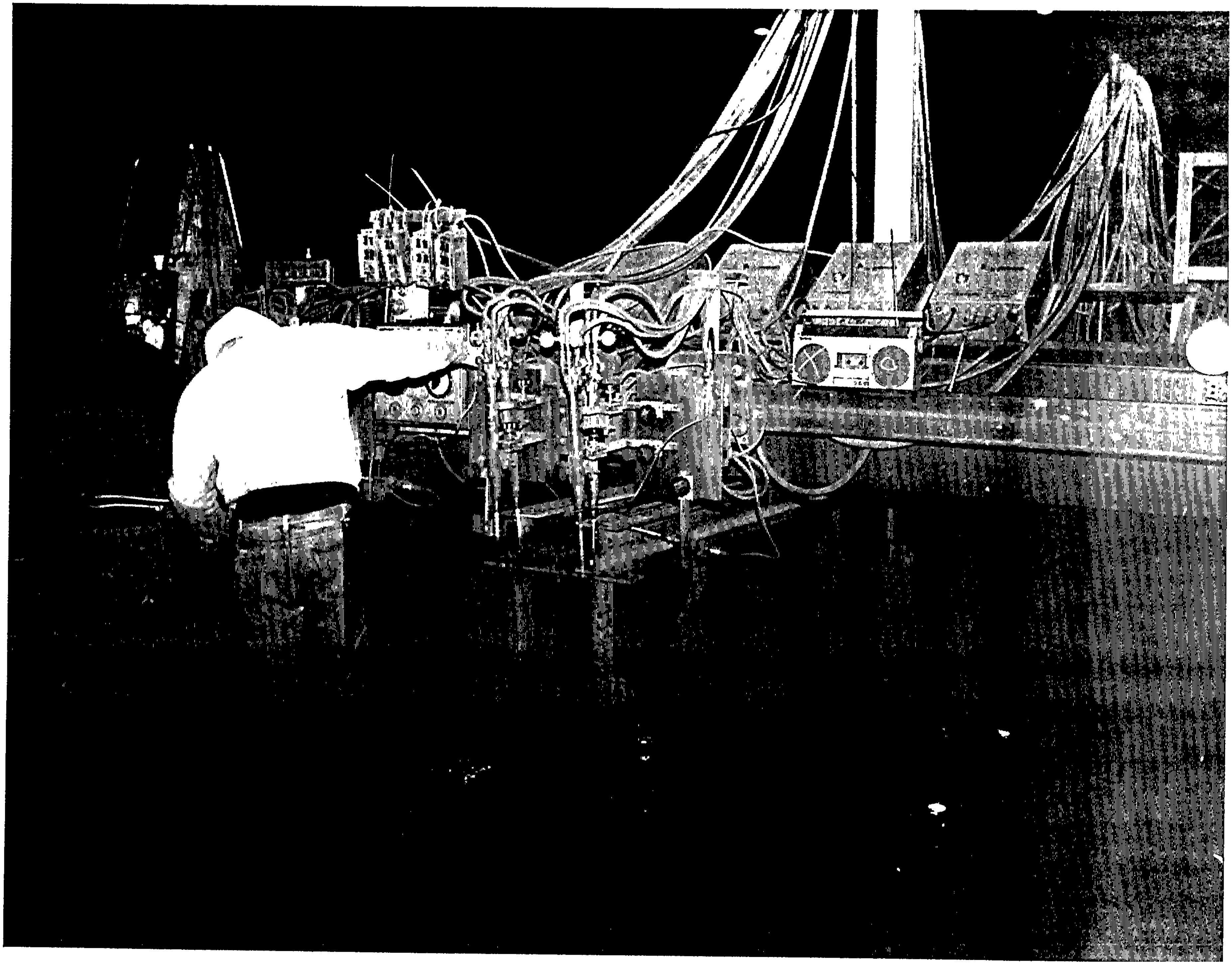
IV Oxyfuel Cutting: deflanging 40-foot I-beams

To provide a baseline of current experience, 6x20# beams eight and forty feet in length were stripped using the OFC process on the gantry device at Bath Iron Works Corporation. Fuel gas used for these tests was “Apachi,” a propylene-based mixture which is widely used as a replacement for acetylene in shipyards and other industries. Flow rates and gas pressures are typically dictated by the size of the cutting tip, which is selected based on the material thickness to be cut. For these tests, a # 1 tip was used. The gantry is provided with electro-mechanical seam tracking devices to control torch position, so that consistently accurate cutting may be performed. The gantry bridge is shown in Figure 13, with one of the seam tracker probes visible under the top flange of the beam in the foreground.

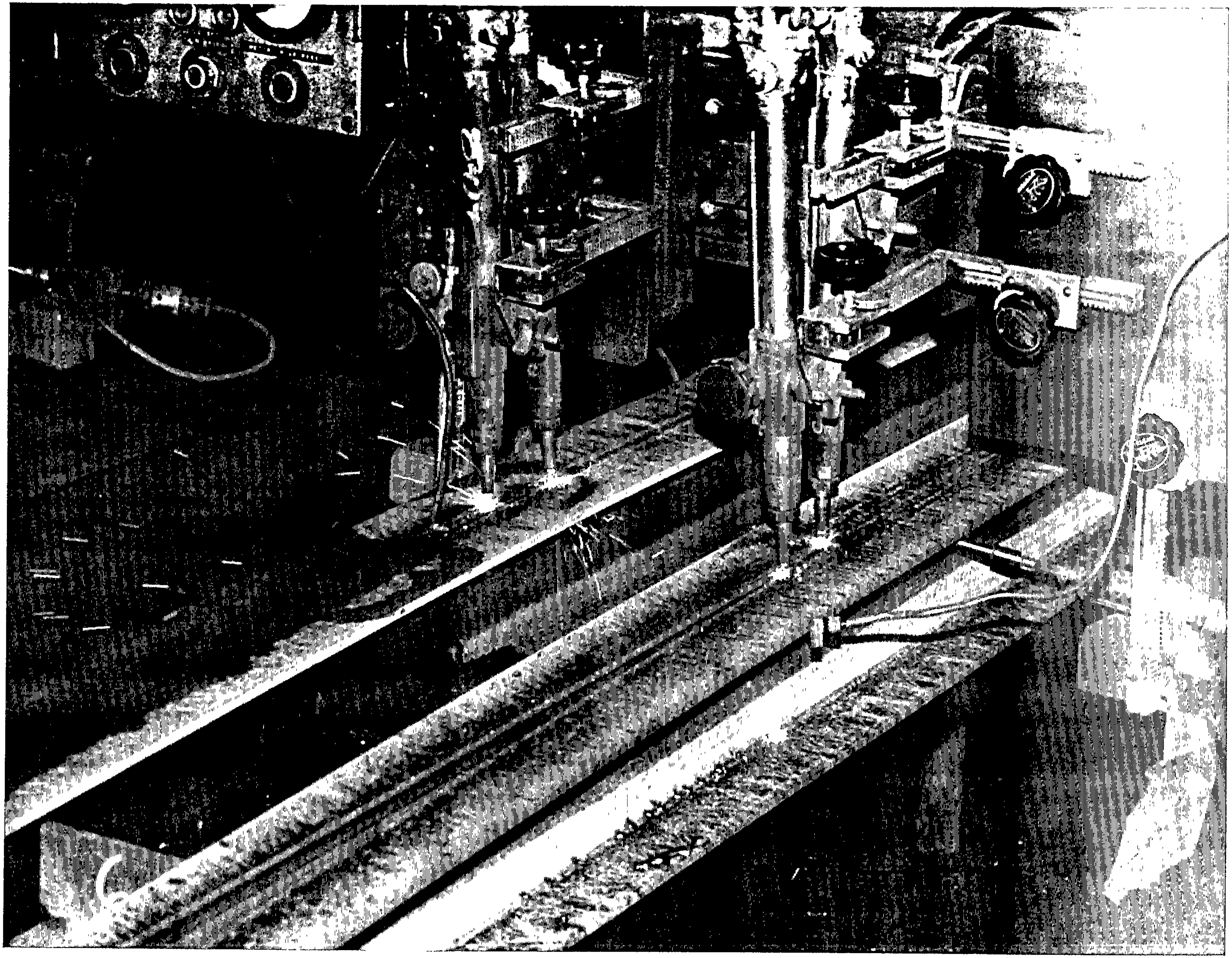
Figure 14 shows this system during the cutting process. The water nozzles are evident on the beam in the background. Experience has shown that this flow rate of water is sufficient to reduce distortion, and that using more water will not produce flatter bars. In this photograph, cutting is being done at approximately 14 ipm, which is typically used for this thickness. Other travel speeds are possible, but were not investigated in this study.

Figure 15 show an as-cut edge. The width of the cut face shows that the cut is approximately 0.06 in. away from the surface of the web. On the right hand side of the photograph, it is evident that some small areas of the cut were unstable and that portions of the cut have “washed” into the web. Had the cut been attempted any closer to the web, it is likely that further damage would have occurred, requiring repair by welding.

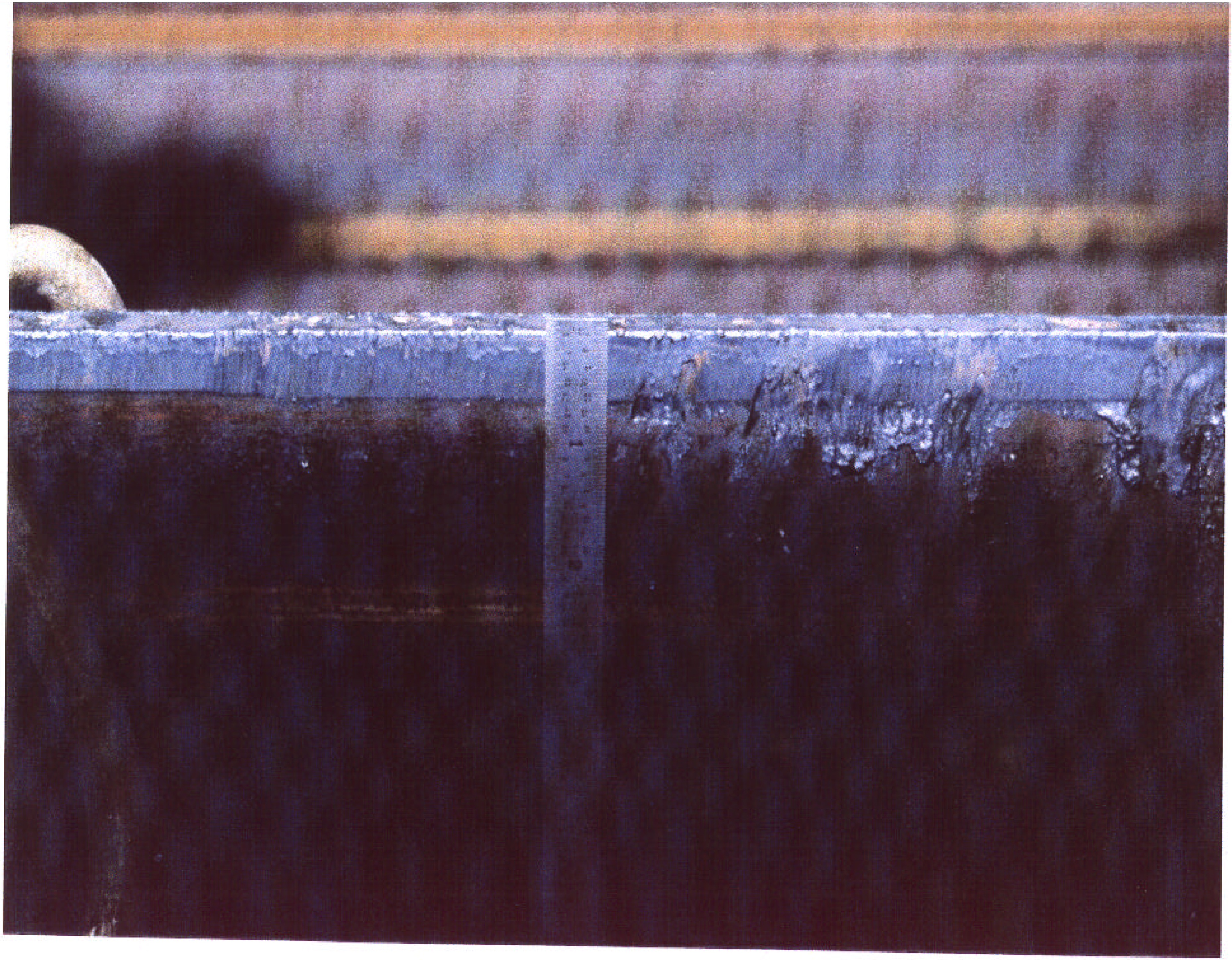
The distortion of the forty-foot test pieces is shown in Figure 16. The improvement offered by the water spray is clearly evident.



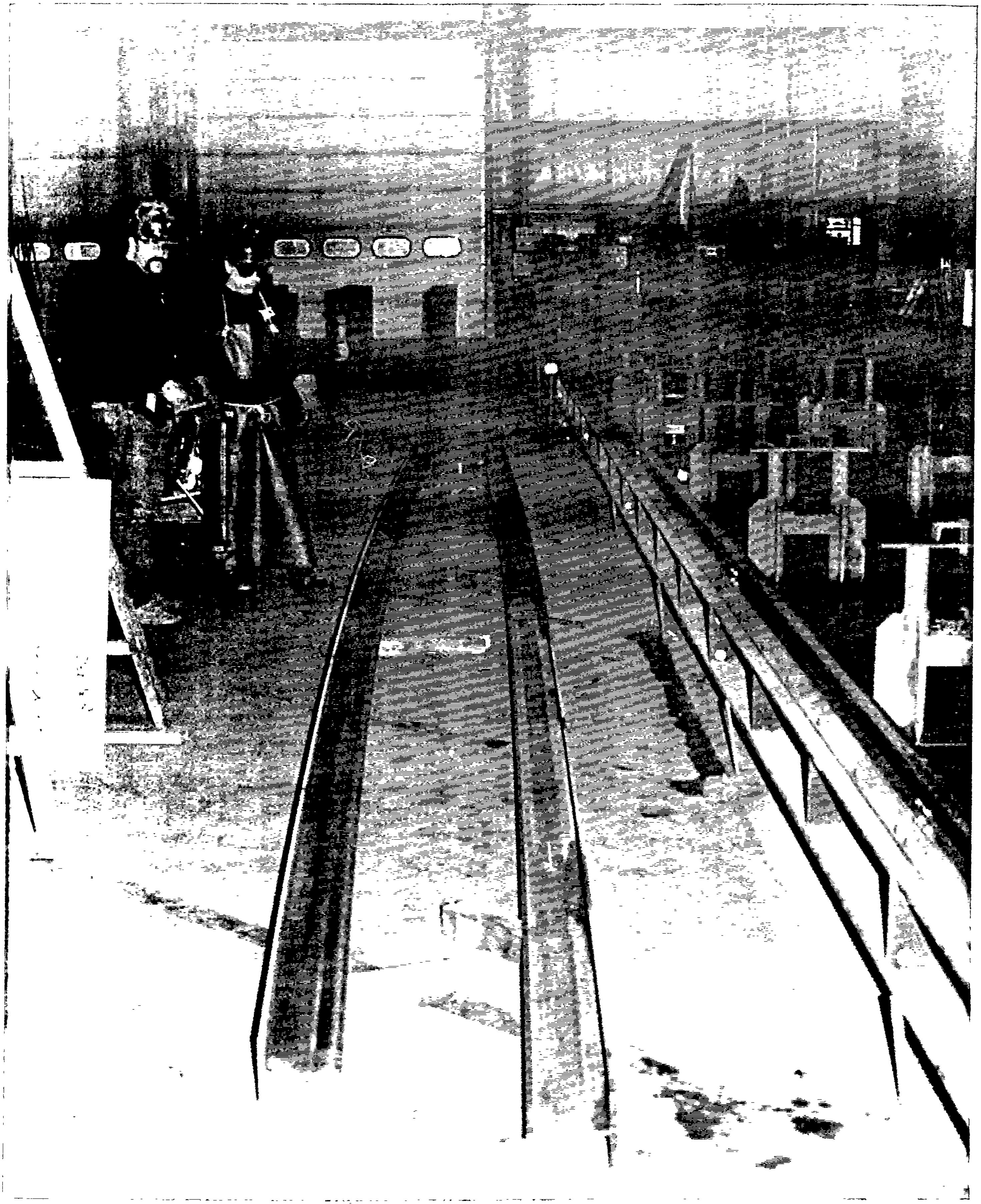
13. Dual-torch heads set up for simultaneous stripping of two W6x20 beams



14. OFC in progress -note water spray on bar in background



15. As-cut surface appearance and width, dual-torch OFC



16. Distortion of dual-torch oxyfuel cut W6x20 beam beams: dry (left) vs. wet (right)

V Plasma Arc Cutting: deflanging 40-foot I-beams

As with laser cutting, there were no facilities available where simultaneous parallel plasma arc cuts could be made. In order to provide a true mock-up of the stripping operation, a large scale mock-up test was arranged with a temporary modification to existing equipment was made.

For these tests, two “Stak-Pak” plasma-arc cutting (PAC) units were loaned to Bath Iron Works by Thermal Dynamics Corporation (manufacturer of this equipment), and were installed on the bar stripping gantry. The OFC torches on one of the carriages were replaced with PAC torches, and all other details of the machine operation were similar. Figure 17 shows the gantry equipped with the plasma equipment.

These particular PAC machines are modular, and were configured to allow cutting at up to 160 amperes. Air and Oxygen were used as plasma gases, with air used as a secondary gas. The best results were obtained with Oxygen.

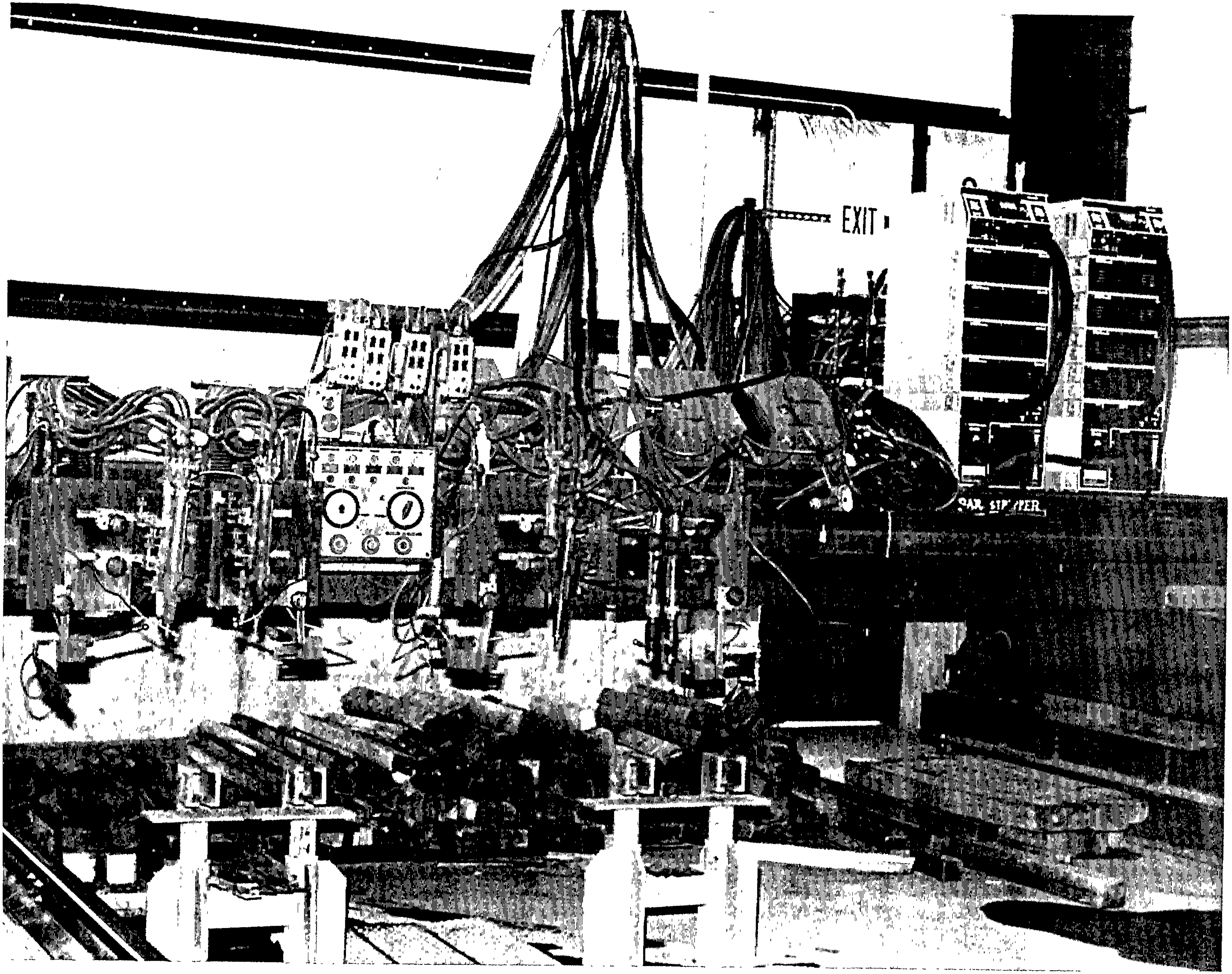
A few trial cuts were made on various material, before starting with the 6x20# beams. It was immediately evident that PAC would produce too much smoke for a full series of tests to be performed during normal work hours. A number of attempts to capture the smoke and fume were made, but were generally unsuccessful, due to the large volume of gas and the particular shape of the I-beam. Because of time constraints on the loaned equipment, it was not possible to separately develop and test a furne capture system capable of operating without producing unsatisfactory levels of contaminant. Water spray was not sufficient to make any difference other than adding clouds of steam to the smoke, and making the process look even worse.

For this reason, it was decided to limit the test to cutting two forty-foot beams, one with water spray and one dry. Testing was scheduled for third shift, and operators were equipped with respirators to prevent exposure to furne. Testing was not done on eight foot parts, since the results of laser cutting and OFC showed such little variation.

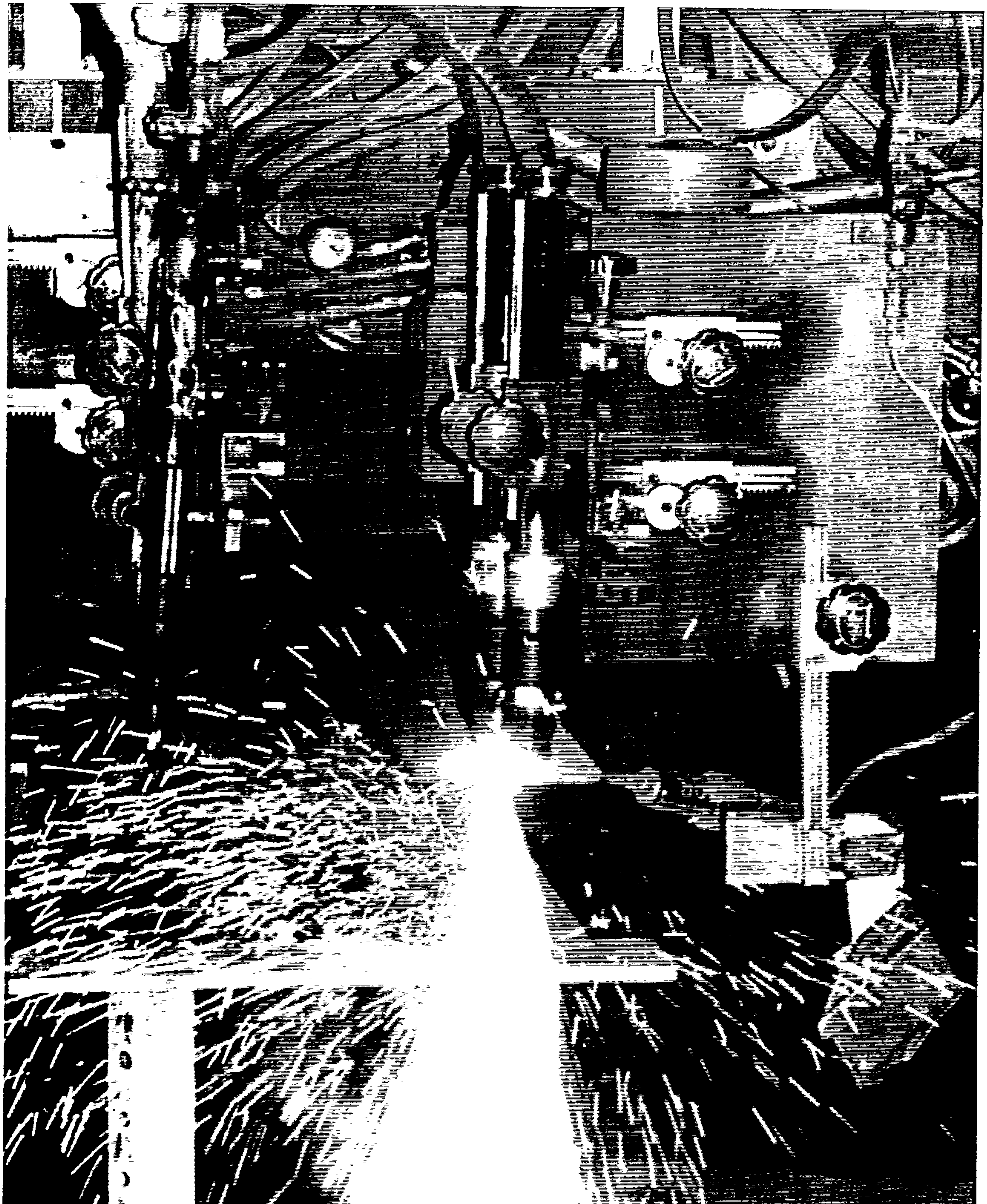
Figure 18 shows the plasma cut at the start, with one torch cutting and the second about to be energized. Figure 19 shows the kerf width of parallel simultaneous test cuts on rusty material. The foreground cut corresponds to the trailing torch, and has a slightly wider kerf, with an additional amount of molten material blown upward. This may be due to the preheating afforded by the lead cut, or may be the result of slightly different parameters or slight variations in nozzle geometry or wear. More testing would be necessary to determine the cause, and to discover optimum nozzle sizes and parameters for I-beam deflanging. Such differential testing was not possible under the circumstances.

Figure 20 shows as-cut appearance of the stripping operation carried out at 58 ipm travel speed and 130 Amperes, using oxygen and air. Dross is slight, and the cut surface is very smooth. A smoother cut face is shown in Figure 21, achieved by dropping travel speed to 32 ipm, with 100 Amperes.

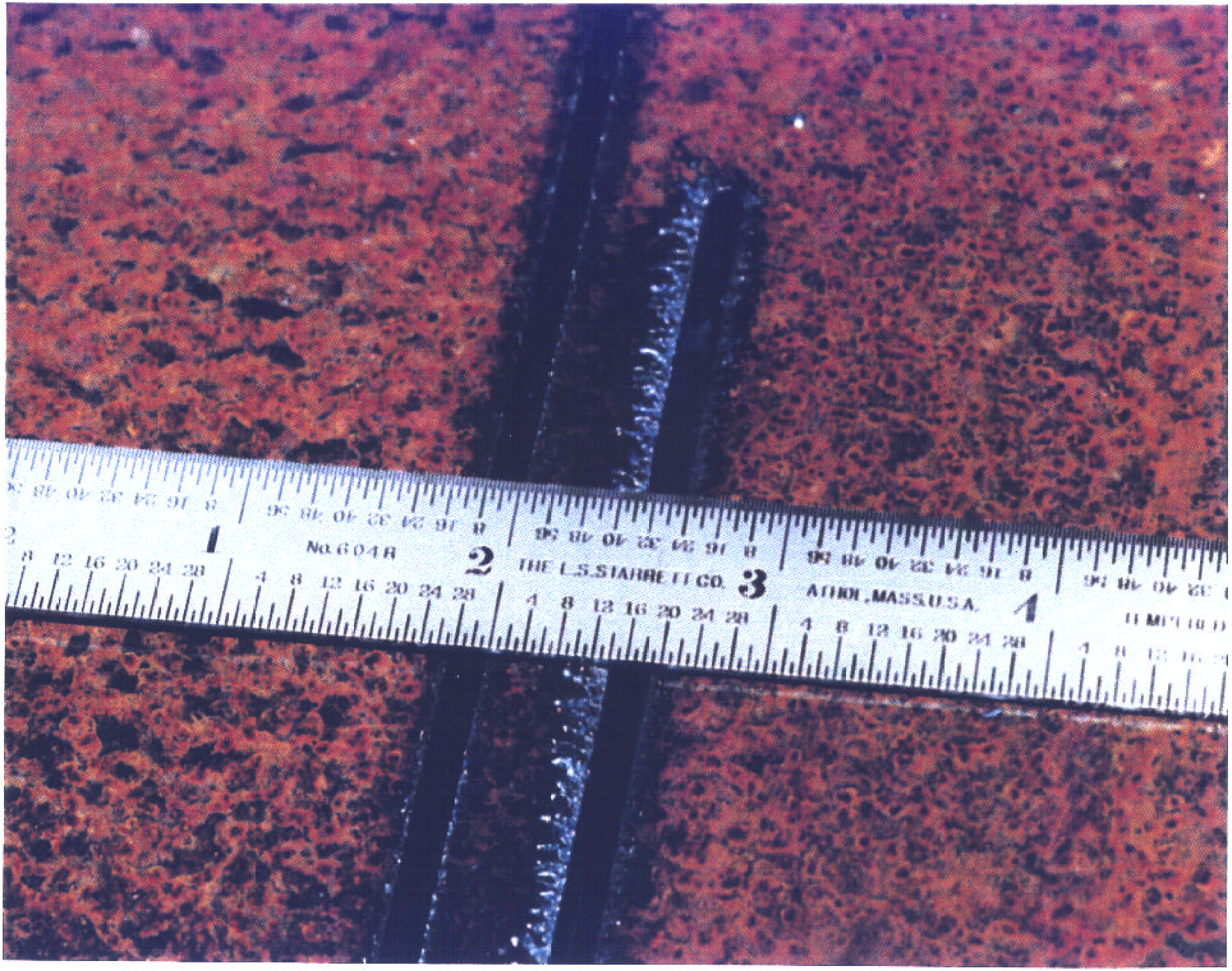
Final distortion of the forty foot bars is shown in Figure 22. Compared to Figure 16, the OFC specimens, the PAC bars are significantly straighter, although the OFC bar with water spray is slightly straighter than the dry-cut PAC beam, as shown in Table I.



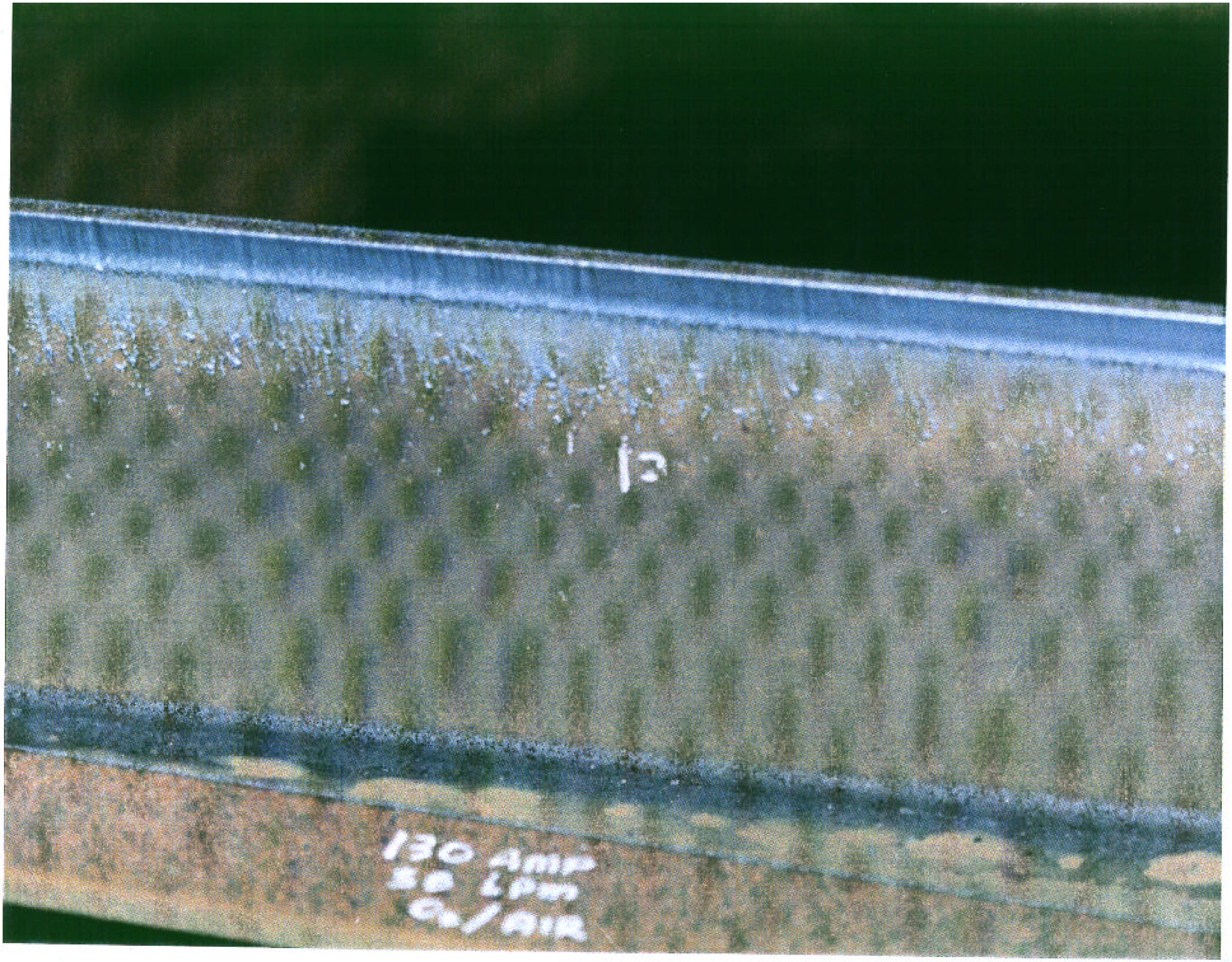
17. Gantry equipped with two PAC torches (powrer supplies on right)



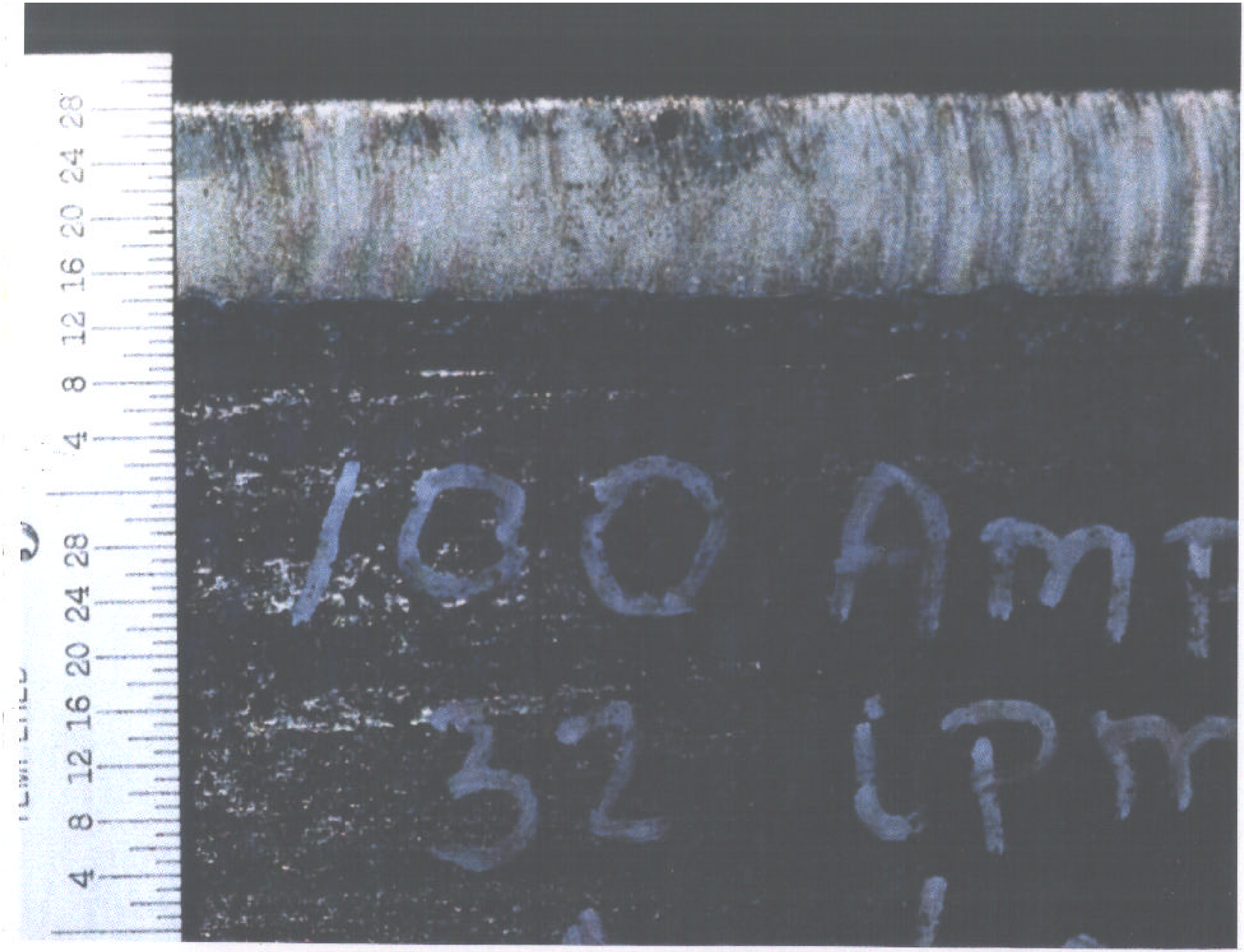
18. Starting Plasma Arc Cuts on 40-foot W6X20 beam



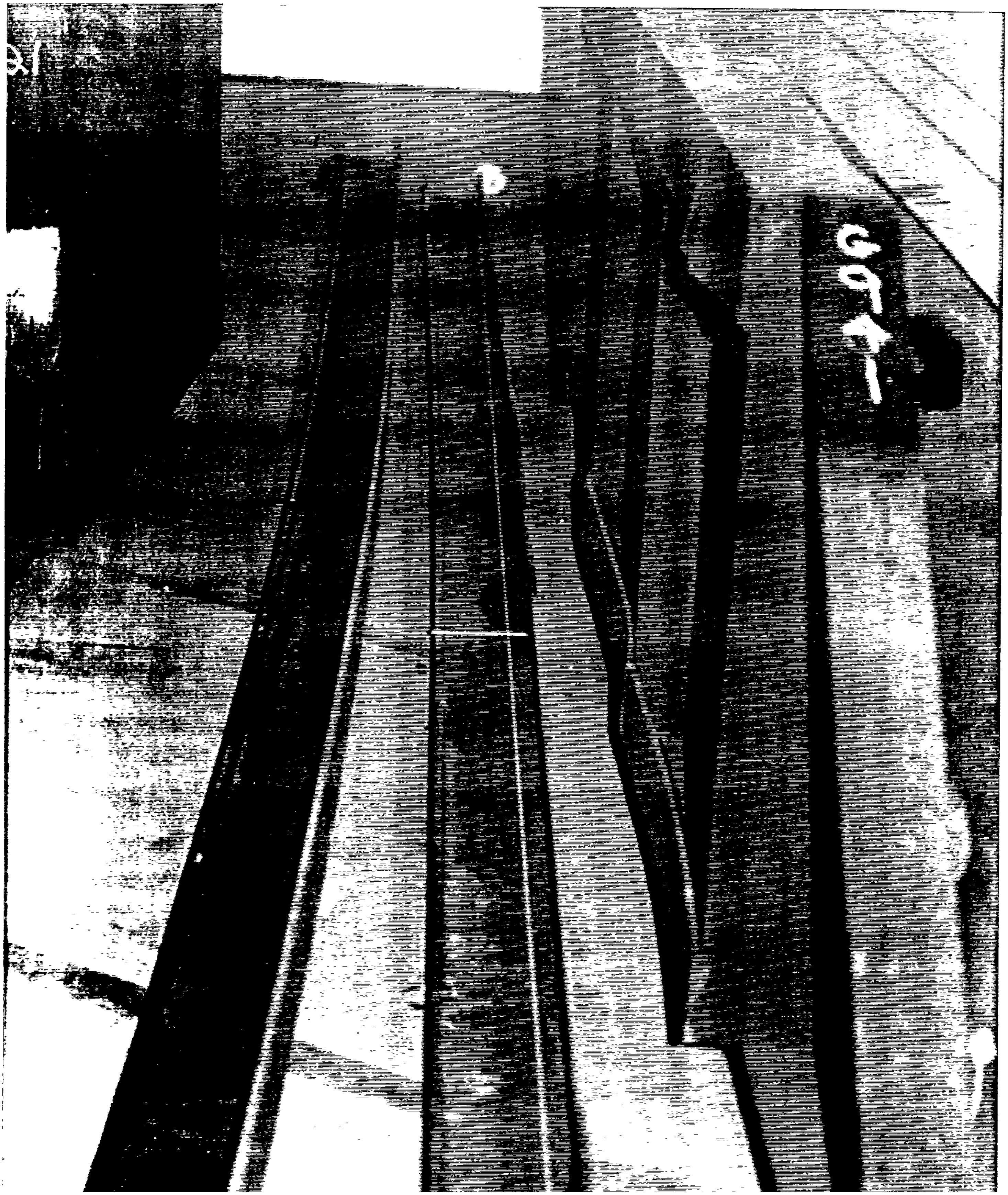
19. Kerf width of simultaneous plasma test cuts on W6x20 beam



20. As-cut surface appearance



21. Cut surface appearance and width



22. Distortion of dual-torch plasma cut W6X20 beam beams, dry (left) vs. wet

VI Laser welding of 20-foot tees

While there is a considerable body of experience with the production of tee shapes using submerged arc welding and dedicated tee-making machinery, there is limited experience in using laser welding for large scale tee manufacturing, especially for making simultaneous laser welds from both sides of a tee joint. At the time of this study, there was no facility available where simultaneous dual laser welding could be done as a demonstration, so a mock-up of a tee weld was made using sequential passes on each side of the web-to-flange joint.

This series of mock-up tests was done at Stardyne, Inc., in Johnstown, Pennsylvania. Stardyne has two 25 kW UTIL C02 lasers, and a side beam fixture capable of holding 30-foot stock. Stardyne had produced a number of tee shapes made from HSLA-80 alloy using this equipment, and did the work for this program at no charge. The fixture does not have any type of adaptive control of seam tracking, but is equipped with a video camera and remote servo devices so that an operator can correct for any deviation of the joint relative to the beam while welding.

For this program test, 20-foot long pieces of mild steel (A-36) flat bar, 3/8-inch thick and 6-inch wide were assembled to simulate the 6x20 I/T shape produced by the stripping operation. The flat bars were prefit to the tee configuration and tack welded on one side of the web using the Gas Tungsten Arc Welding (GTAW) process. The tacked shapes were loaded into the side beam fixture, with the untacked side positioned so as to be the first to be welded. This equipment is shown in Figure 23. After welding the first side, the bar was removed from the fixture and repositioned for welding of the second side. Tack welds were remelted in the laser weld pass.

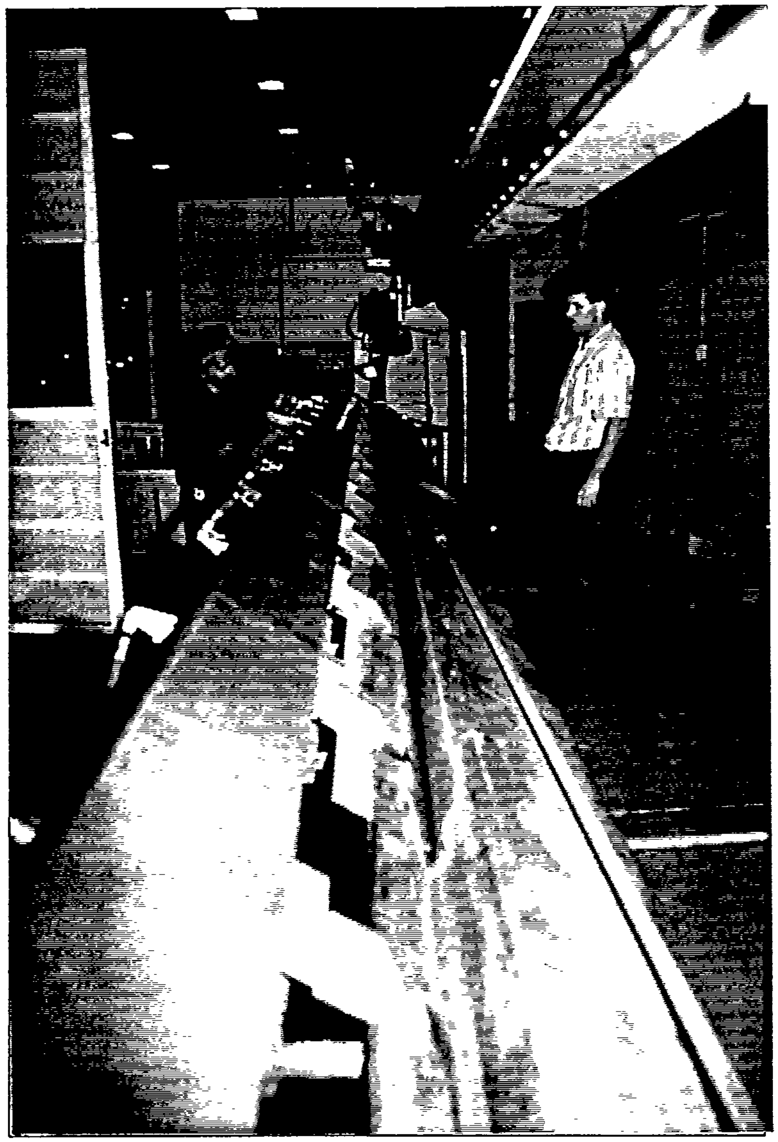
Two tees were produced, one using autogenous welding, and the other welded with added filler metal. Type E1OOS-1 filler metal was used, due to availability, and since metallurgical testing was not planned, it was felt that this filler would provide a reasonable test of travel speeds and wetting actions. All joints were welded with a single pass from each side.

Welding was carried out at approximately 9 kW laser power, using helium gas at 80 cfh for plasma suppression. Autogenous welds were made at 59 ipm travel speed, and joints with filler metal were welded at 36 ipm. The weld with filler metal had to be stopped and restarted a few times due to a problem with the wire feeding mechanism. Because tracking while adding filler metal was generally more difficult, the lower travel speed was selected.

Figures 24 and 25 show the tee made by autogenous welding. Although the weld leg length is on the order of l/8-inch or less, the ability to produce complete penetration has previously been demonstrated on joints similar to this. Figure 24 shows that there is little distortion resulting from the autogenous weld. In Figure 25, some undercut can be seen.

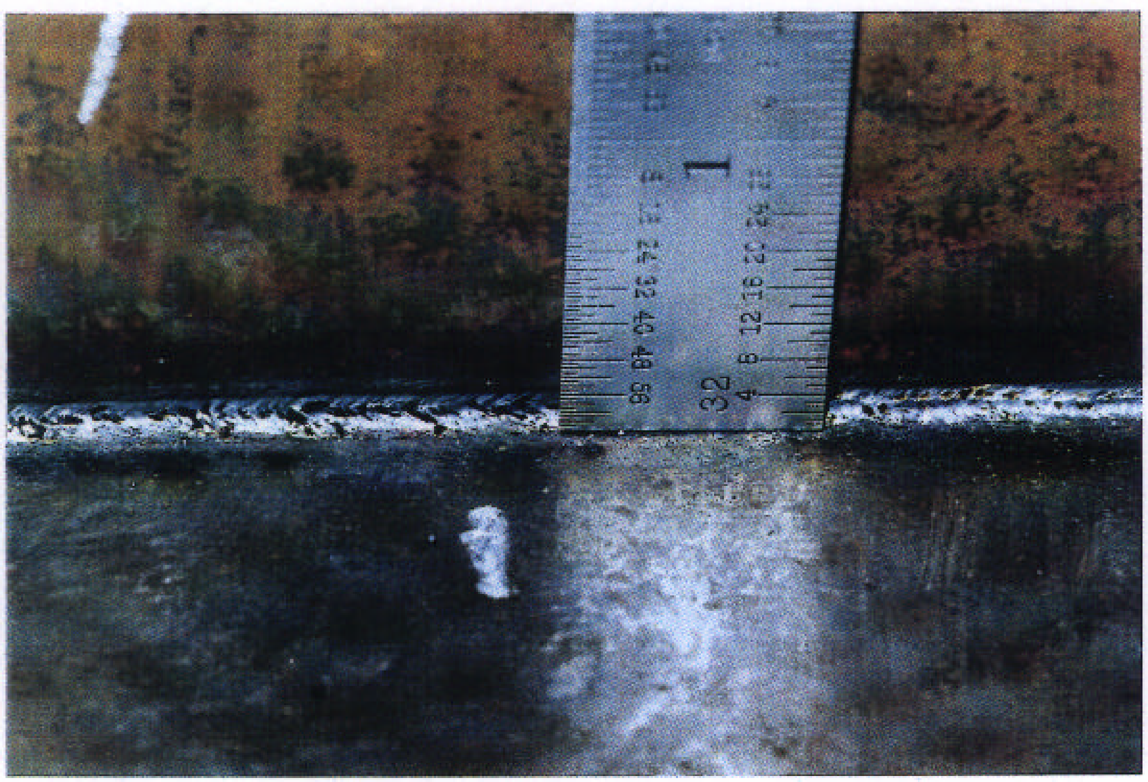
Figures 26 and 27 show the tee welded with filler metal. In Figure 27, an area where the weld was stopped and restarted can be seen. The use of filler metal has produced a weld reinforcement with larger leg size, and reduced undercut. Although the surface is somewhat concave, fill penetration has been demonstrated at these power levels and speeds, also. Figure 26 shows that this tee has more camber than that produced by autogenous welding. Although the shrinkage of filler metal is a likely cause of this added distortion, the reduced travel speed has undoubtedly played a part as well.

The limited scope of this program and the high operational cost of this equipment did not allow the performance any detailed matrix testing to optimize weld contour or reduce distortion. This, and the development of a capability to simultaneously weld both sides of tee joints accurately at higher speeds would be useful areas for further work.

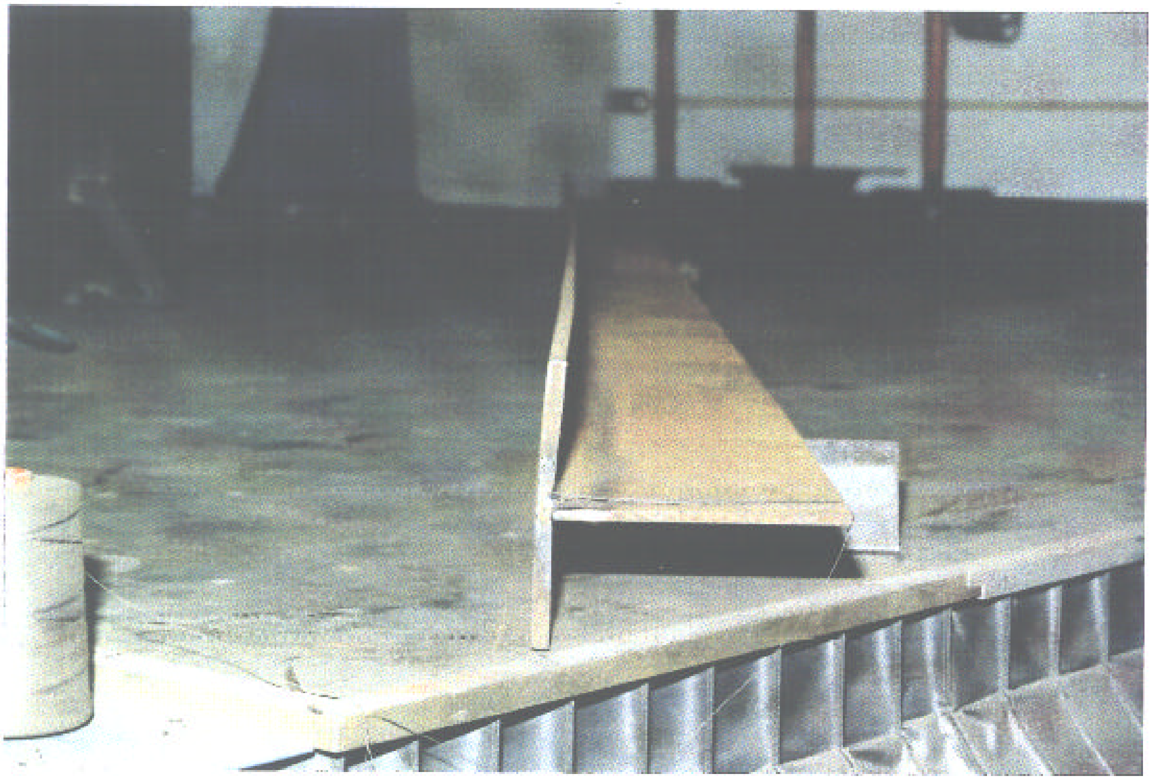


23. **Side beam fixture at Stardyne with 25 kW C02 laser, set up to weld**

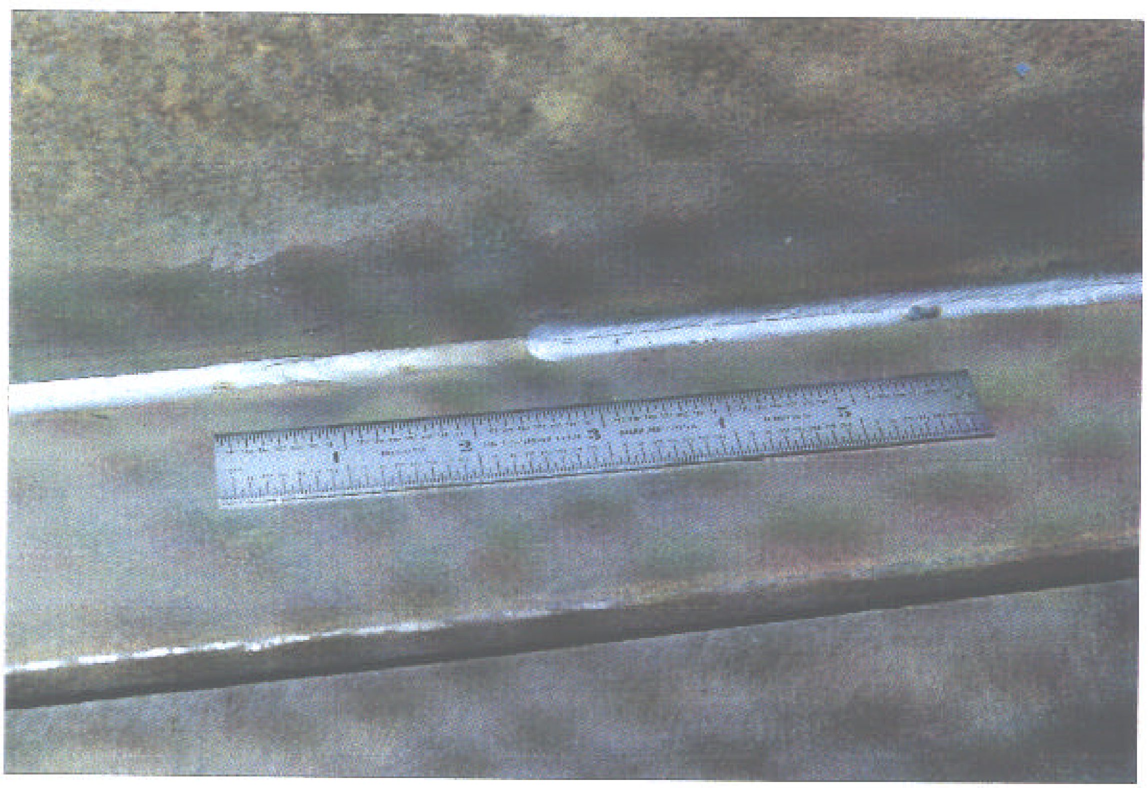
24. Tee section made of 3/8x6 inch flat bars, autogenous weld



25. Close-up of autogenous weld



26. Tee section made of 3/8x6 inch flat bars, welded with filler metal



27. Close-up of weld

VII Submerged arc welding of lightweight 49-foot HSLA Tee sections

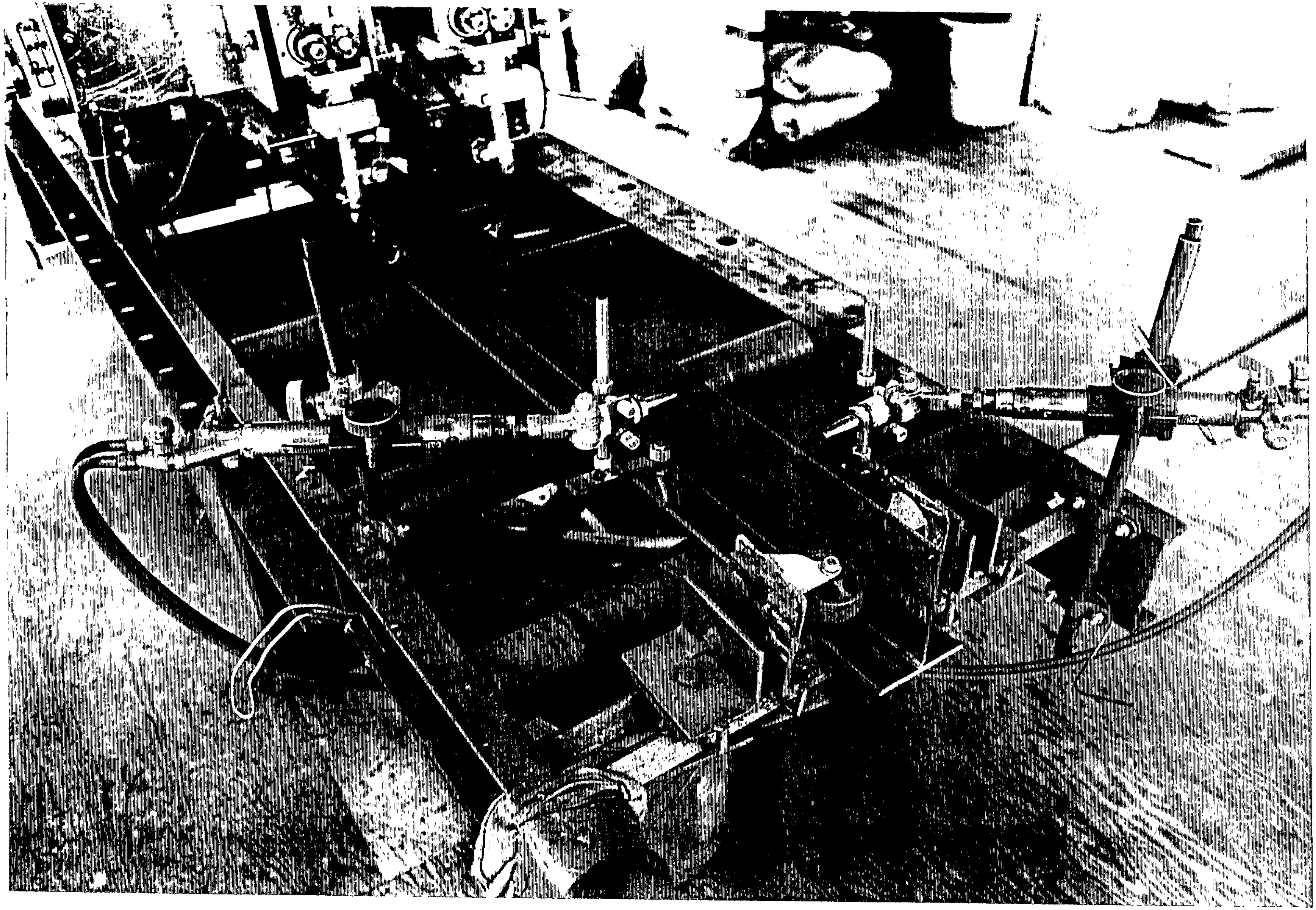
During the AEGIS Guided Missile Cruiser (CG-47 class) construction program, several thousand feet of lightweight tees were fabricated from HSLA-80 alloy by High Frequency Resistance Welding (HFRW). The use of these tees were part of a weight reduction effort in which hot-rolled tees were replace with lighter fabricated shapes. During the lengthy approval cycle, the need for the fabricated shapes dictated that several shipsets of these tees be produced by conventional welding methods. The equipment shown in Figure 27 and 28 was used to produce more that twenty-one miles of tee sections similar to those shown in the photographs.

This information is presented here to document the production of lighter weight tee shapes at high speeds with low distortion and excellent weld quality, and minimum labor cost. When the HFRW process was certified, this equipment was dismantled.

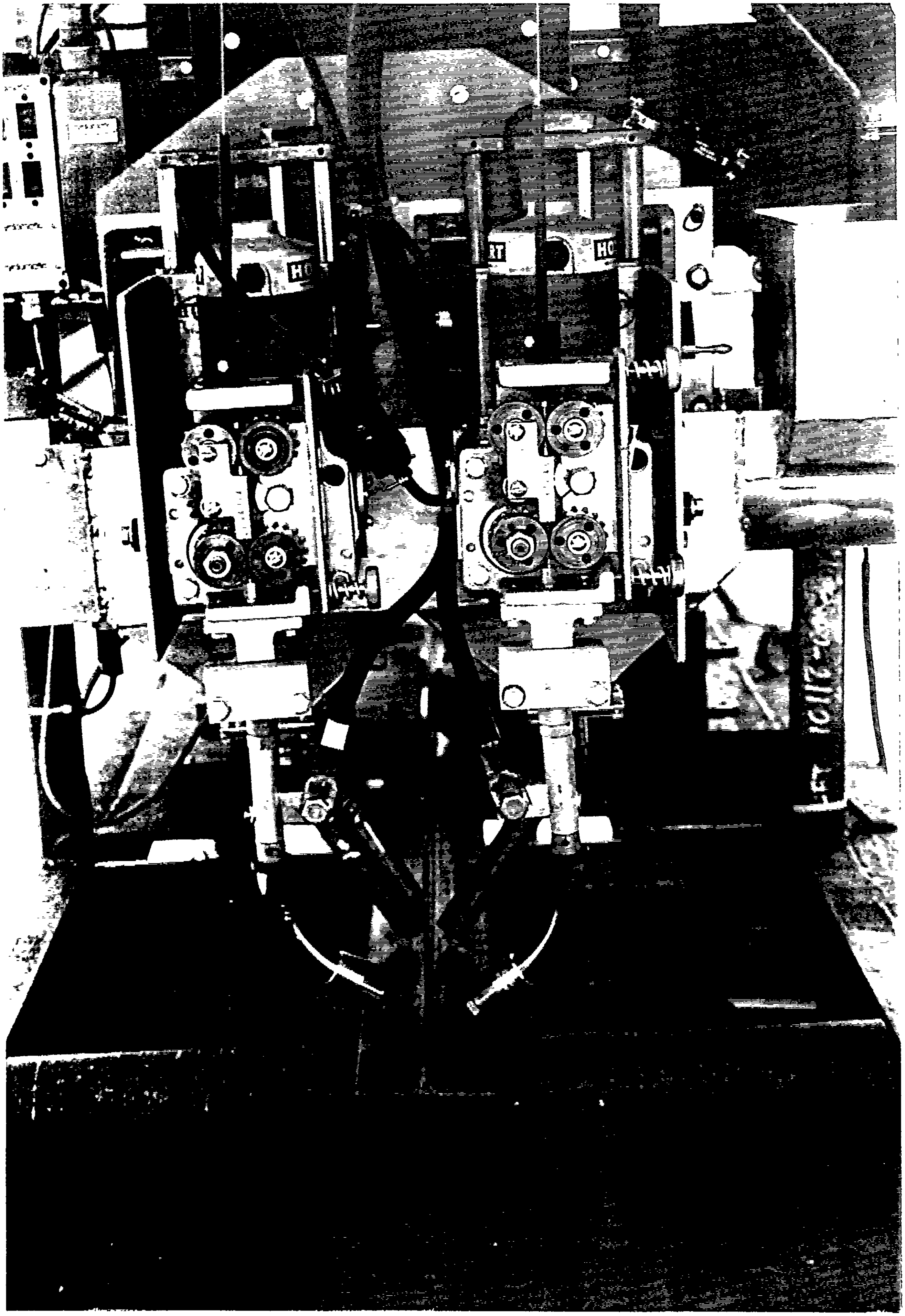
The submerged arc welding (SAW) process was used, operating at 300 amperes and 29-30 volts. Material traveled past stationary heads at 66 ipm, the maximum travel speed allowed by the motors in the machine. Electromechanical seam tracking was provided to keep the welding head accurately aligned with the joints at these speeds. For this application, Mil-100S-l filler metal was used with a compatible flux. Fillet welds produced exhibited fill penetration and a leg length of just over 5/32 inch, with a flat contour, and the smooth surface typical of SAW.

Wire brushes and flux-recovery equipment, not shown in the photographs, were provided to keep speeds up and reduce the amount of manual labor on repetitive tasks. Oxy-fuel torches were used to provide balancing heat to the opposite edges of the web, and virtually no post-weld straightening was required.

Two operators produced from 1200 to 1500 feet of completed tees each day. Production was limited to one shift, and the machine ran continuously except for lunch breaks. Production ceased in the afternoon to allow removal of completed stock and to load in new material for the next day’s production.



27. Overall arrangement, showing welding heads and straightening torches



28. Detail of welding torches, flux nozzles, seam tracker and wire feeders

TEE BEAM MANUFACTURING ANALYSIS

FOR

WEIGHT REDUCTION AND PRODUCIBILITY

NSRP PROJECT #N7-91-4

APPENDIX A

ENGINEERING EVALUATION

for

SOCIETY OF NAVAL ARCHITECTS AND MARINE ENGINEERS

SHIP PRODUCTION COMMITTEE

PANEL SP-7, WELDING

Brian W. Miller, Senior Structural Engineer

Bath Iron Works Corporation
700 Washington Street
Bath, Maine 04530

July 30,1992

Revised JuIy 23, 1993

TABLE OF CONTENTS

SUMMARY

The results of this evaluation readily show that welded Tee stiffeners can be designed to replace existing stripped Tees with a substantial resultant savings in weight and the quantity of material used. In addition to increased flexibility of application, other benefits which may be realized through the use of welded Tees are increased dimensional control and lower distortion levels.

An overalI stiffener area reduction of 18% could be expected if welded Tees were substituted for the currently used stripped Tee panel stiffeners throughout a DDG 51 Class ship.

For DDG 51, this reduction in stiffener area would result in an overall ship structural weight savings on the order of 46 long tons. However, an overall application of welded Tees would very likely have the negative effect of raising the ship's vertical center of gravity.

DDG 51 hull girder longitudinal strength properties could be expected to decrease by about 2.1% if reduced area welded Tees were substituted for the current longitudinal stiffening in the hull of the ship. Longitudinal strength reserves for DDG 51 are large enough to accommodate this decrease in strength properties.

CONCLUSIONS

The results of this evaluation indicate that weight and material savings for DDG 51 Class ships are indeed possible through the substitution of welded Tee panel stiffeners for the currently used stripped Tees. If all the stripped Tees in a DDG 51 Class ship were replaced with welded Tees it is reasonable to expect an approximately 46 long ton decrease in ship structural weight and in addition a decrease in scrap of approximately 170 long tons.

To positively impact the vertical center of gravity (VCG) of the DDG 51, application of weight saving welded Tees would have to be made judiciously - that is, above the ship's VCG (about 23.7' above baseline).

Retrofitting panel stiffeners would be costly, but applications for welded Tees may exist in the future expansion and growth of the DDG 51 design. Examples might include the helicopter hangar planned as part of a Flight IIA upgrade or the potential future reduction of the ship's nuclear blast resistance requirements. The latter case holds special promise since welded Tees would allow the weight of a stiffener to be reduced while maintaining the envelope dimensions (D and WF). This would minimize the impact to lofting, distributive systems and outfitting.

Savings above those stated above may also be possible through further reductions in the web thickness (TW) of a welded Tee stiffener. In most stiffened panel cases, bending strength requirements govern the stiffener selection and currently that selection must be made from a list of stripped wide flange sections. These wide flange sections are dimensionally configured for versatility of application - some of which shear strength may govern. The web thickness (TW) is sized to meet a minimum value which will assure that the web does not fail by shear instability. Often in ship stiffened panel applications where bending strength governs, the calculated shear loads and shear stresses are very low. It is possible to argue that web stabiIity is assured by low calculated stresses and web thicknesses thinner than the minimum guideline for stability may be used.

CONCLUSIONS - Continued

Weight savings and applications beyond those investigated in this evaluation are possible if the flange width (WF) and depth of section (D) can be tailored to the application.

Potential Growth in Other Areas - Commercial design work currently taking place at Bath Iron Works could take advantage of welded Tee technology. Deck stiffeners required for the design need to have the following characteristic:

- A simple shape to minimized fitting costs
- A low profile to maximize headroom
- High bending strength (with relatively low shear strength) to support large loads on long continuous spans
- Long bar lengths to minimize excessive butt joints

Plans for using bulbed flats, split channels and flanged plates for stiffeners all have drawbacks including excessive weight, lack of dimensional control, material availability and joining difficulties. An angle shape, using the welded Tee technology, with the flange and web thickness sized independently to meet the required strength, seems to be an ideal answer for this application.

Also not covered here but an area with potentially widespread application is the mixing of materials for the flange and web components of a welded Tee section. The advantages offered are weight and potential cost savings as well as the ability to tailor stiflener materials to support subsequent connections to the stiffeners with standard welding methods.

PURPOSE

The purpose of this report is to investigate the engineering feasibility of substituting welded Tee shapes for rolled and flange stripped Tees currently used on DDG 51. This report seeks to show that material and weight can be saved by using welded Tees while meeting the structural requirements of the ship's construction specification (ref. 1).

This report also will present and discuss other potential applications for the use of welded Tees in both U.S. Navy and commercial ship building programs as well as other stiffened panel applications.

BACKGROUND

This report and investigation provide the structural engineering justification for substituting welded Tee panel stiffeners for the currently used stripped Tees. This is part of a larger effort underway to explore weight and cost savings as well as other advantages of using welded Tee sections rather than stripped Tees for panel stiffening.

A savings in the weight of the Tee sections used to stiffen panels will lead to an overall reduction in structural weight. Developing Tee sections tailored for specific applications, weld fabricated in almost limitless variations from plate or strip, offers a potential way to save structural weight.

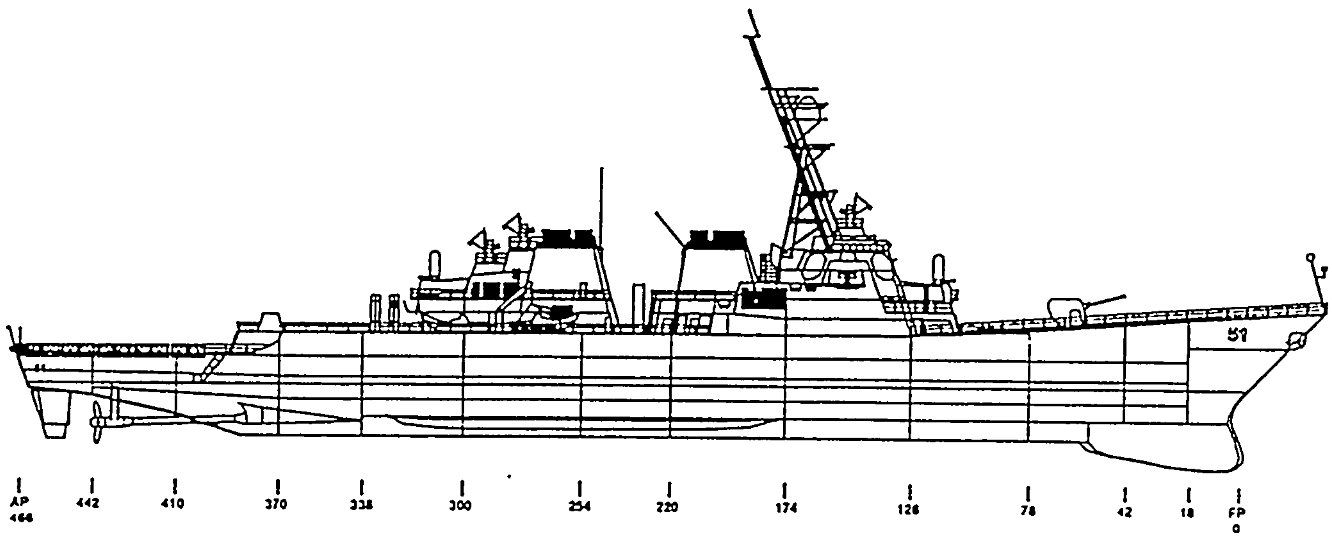
The current practice of making the Tee sections used to stiffen panels by stripping off and scrapping the flanges of standard wide flange beams is costly in several respects. In addition to the high scrap rate, the burning process used is somewhat slow and involves sufficient heat input to the product to cause distortion in the free edge of the web of the Tee. This distortion can result in subsequent fitting difficulties and lack of dimensional consistency.

The concept of weld fabricating Tee sections may not be entirely new, but advances in welding technology inculding laser welding equipment and faster weld travel speeds strengthen the feasibility of welded Tee sections.

SCOPE OF INVESTIGATION

For purposes of providing structural engineerig justification for substituting welded Tee panel stiffeners for the currently used stripped Tees, an investigation of stiffened panel applications in the design of the DDG 51 was conducted. The panels which were selected and are presented in figure 1.

Selection of stiffened panels for investigation was based on several factors. The shell and deck longitudinal panels which were selected involve stiffener sizes which comprise approximately 26 percent by weight of the stripped Tees used on DDG 51 and therefore offered the largest potential weight savings. Location of panels in the ship structure influenced selection in that weight savings above the ship's center of gravity would be potentially more valuable. Panels were also selected based on their representation of typical loading. The stiffened bulkhead panels selected represent typical main watertight transverse bulkheads throughout the ship. Stiffened shell and deck panels are also representative of configurations typical throughout the hull of the ship. Specialized structures with unique load carrying requirements were in general not investigated.



DECK LONGITUDINAL STTFFENERS

Interior Decks
Platforms
Weather Decks

SHELL LONGITUDINAL STTFFENERS

Above the Waterline
Below the Waterline

STRUCTURAL BULKHEAD STTFFENERS

Transverse Bulkheads

Figure 1. Scope of Investigation for DDG 51 Class ships

SCOPE OF INVESTIGATION - Continued

Based on the engineering evaluation, an effort is made in this investigation to determine quantitatively the weight savings which might be realized using welded Tee sections for panel stiffening as opposed to the stripped wide flange sections currentIy in use.

CRITERIA USED FOR ENGINEERING EVALUATION OF DDG 51 STIFFENED PANELS

Configuration and Dimension Criteria - The DDG 51 design is a complete production design. Changes at this point which impact lofting, distributive systems and outfitting are very costly. For this reason, when evaluating DDG 51 applications, it was assumed that any welded Tee which would be developed should have the same basic envelope dimensions as its currently used counterpart. Both the section depth (D) and the flange width (WF) would be maintained at the current values (figure 2).

Although material can be special ordered from a mill, this evaluation assumes that plate, sheet or strip components of standard thicknesses would be used for welded tees (table 1). Other guidelines which were used to develop the component thicknesses for welded Tees are summarized in table 2. It was also assumed that no change in the panel plate thickness would take place.

5/16 inch (.313”) plate
1/4 inch (.25”) plate
3/16 inch (.188”) plate
8GA (.1644”) sheet or strip
10GA (.1345”) sheet or strip
11 GA (.1196”) sheet or strip
12 GA (.1046”) sheet or strip

Table 1. Standard Component Thicknesses for Welded Tees

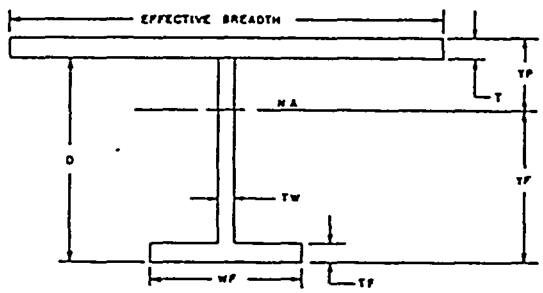


Figure 2. Typical Stiffened Panel Configiration

Minimum Outstanding Flangc Thickness to Assure Flange Stability	$TF \geq WF \times \sqrt{Fy/E}$	ref. 5
Lateral Support of Flanges to Prevent Lateral Buckling	Function of Span/WF and WF/D (No changes to these values)	ref. 5
Minimum Web Thickness to Prevent Shear Buckling	$TW \geq (D - TF)/53.7$	ref. 7&8

Table 2. Web and Flange Thickness GuideLines for Welded Tee Development

CRITERIA USED FOR ENGINEERING EVALUATION OF DDG 51 STIFFENED PANELS - Continued

Weight Criteria - While not currently a strong concern on DDG 51 class ships, weight reduction is a worthwhile goal in almost any U.S. Navy surface combatant. In addition to the more immediate benefits such as fuel savings, reduced weight provides a margin for future growth in the ship's capabilities. The penalty for exceeding the contractual weight limit for DDG 51 was $25,000 per long ton not to exceed $750,000. For the DDG 51 class a more important goal is a reduction in the ship's vertical center of gravity (KG). To maintain margin for future growth in combat capability, tight restrictions on excess high weight have been imposed. For DDG 51, the penalty for exceeding the contractual limit on vertical center of gravity was $1.25 million per each tenth of a foot.

Material Criteria - The current design for DDG 51 class ships uses primarily high strength steel shapes with a yield strength (Fy) of 51,000 psi for panel stiffening. This engineering evaluation assumes that the components of a welded Tee section would have the same strength and related material properties.

Local Strength Criteria - In general, due to span length and distributed load profiles, plate stiffener combinations used on DDG 51- are sized based on bending strength requirements. The exceptions may be found in the deck house web frames which must resist large blast loads and shear strength may govern and in areas where special vibrational characteristics are required and the stiffness (moment of inertia) of the plate stiffener combination governs.

Panel thickness is dictated by the loading as well as the stiffener and web frame spacing. Stiffeners, usually Tees stripped from wide flange shapes are then sized based on the minimum bending strength (flange section modulus) required of the plate stiffener combination. The selected combination must have a calculated flange section modulus equal to or greater than that required.

Since, the selection of stripped Tee sections available is limited, the margin between the provided strength and that required may be large enough to offer significant weight reduction if it could be reduced. A welded Tee, with the flexibility that its web and flange thickness can be sized specifically to meet the strength requirements, offers potential for weight reduction.

ENGINEERING EVALUATION APPROACH

The plate stiffener combinations selected as candidates for welded Tee beam application have been evaluated using two separate approaches. The first approach seeks to satisfy the strength requirements for the candidate plate stiffener combination with a welded Tee. The second approach seeks to match the bending strength of the current stripped Tee section with a welded Tee section of lower cross sectional area.

The use of computer programs in this evaluation is limited. Lotus spreadsheets were used to calculate section properties of the welded Tee sections and for other repetitive calculations.

ENGINEERING EVALUATION APPROACH - Continued

Satisfy the Required Bending Strength - In this approach, the welded Tee section has been sized to meet the calculated required bending strength or required combined bending and axial strength for the section. Shear stress was calculated for each of the welded sections to assure that the allowable shear stress had not been exceeded. As would be expected, the calculated shear stresses were usually low.

The load matrix for each of the plate stiffener combinations considered was developed form the requirements of reference 1. A summary of these requirements is presented in table 3. Guidance for load application and span end fixity was taken from reference 5.

	Ship Bending (100a)	Design Hydrostatic (111b)	Tank Pressure	Wind 30#/ft^2 (070c)	Snow & Ice 7.5#/ft^2 (070c)	Wave Slap 500#/ft^2	Docking Loads	Nuclear Air Blast (100a)	Gun/Missile Blast (100a)	Storm Loads (070c)	Dead Loads	Live Loads	Flooding	Aircraft (588)	Interior Overpressure (CPS)	Dolly Pallet Loads (130b)
SHELL																
Below Waterline	●	●	●				●			●	●					
Above Waterline	●	●	●					●		●	●					
DECK																
Interior Decks	●		●							●	●	●	●		●	●
Platforms	●									●	●	●			●	●
Weather Decks	●	●			●	●		●	●	●	●	●		●	●	●
STRUCTURAL BULKHEADS																
Longitudinal	●		●					●		●	●		●		●	
Transverse			●					●		●	●		●		●	
Miscellaneous			●												●	
SUPERSTRUCTURE																
Longitudinal Deckhouse				●		●		●	●	●	●				●	
Transverse Deckhouse				●		●		●	●	●	●				●	
Interior Decks										●	●	●			●	●
Weather Decks								●	●	●	●	●			●	●

Table 3. Loading Matrix for Selected Plate Stiffener Combinations (Reference 1)

ENGINEERING EVALUATION APPROACH - Continued

Match the Bending Strength of the Existing Section - In this approach, the welded Tee section has been sized to match the bending strength (as indicated by flange section modulus) of the currently used stripped Tee while minimizing overall area of the Tee. Combined bending and axial stresses as well as shear stresses were checked to assure that allowable values had not been exceeded.

Allowable Material Stresses - Allowable stresses for this evaluation were taken from references 1 and 3 for high strength steel (Fy=51,000 psi).

Allowable Bending Stress (Fb) = 40,000 psi [reference 1]

Allowable Compressive Stress (Fc) = 0.67 Fc' for KL/r >60
(Fc) = 0.80 Fc' for KL/r <60
[values for Fc' from figure 1, reference 3]

Allowable Shear Stress (Fv) = 24,000 psi [reference 1]

RESULTS OF EVALUATION

A summary of the results for the plate stiffener candidates selected using each of the evaluation approaches discussed in the preceding section is presented below in table 4. Reference 10 includes the calculation details which support the reported results.

The results of this evaluation clearly show that a reduction in stiffener area and therefore material and weight could be realized by using welded Tees instead of the currently used stripped Tees: Overall average stiffener area savings indicated by satisfying the calculated strength requirements is 18%. Stiffener area savings of 6% is indicated when the strength of the currently used stripped tee section is matched.

A greater percentage of stiffener area reduction is indicated for welded Tee application above the ship's vertical center of gravity (VCG). When satisfying strength requirements, indicated stiffener area savings above the ship's VCG is 24% and below the ship's VCG is 13%. Similar results are indicated when matching the strength of the existing section. Stiffener area savings above the VCG is 9% and below the VCG is 3%. While this ratio may seem encouraging, especially for the DDG 51 where a reduction in VCG would be considered very valuable, these results are mitigated somewhat in that most of the stiffener area is located in the lower portions of the ship. In this evaluation, the existing Tees had an average stiffener area of 2.81 in^2 below the ship's VCG and 1.81 in^2 above the VCG.

SHELL LONGITUDINAL BELOW WATERLINE ABOUT MIDSHIP (FRAME 233)
(Located below the ship's verticaf center of gravity)

CONFIGURATION	D(in)	WF(in)	TW(in)	TF(in)	$A_{stiff}(in^2)$	$I(in^4)$	$SM_{flg}(in^3)$	$A_{shear}(in^2)$
12 x 4 x 14# I-T w/.5O" plate	11.91	3.97	.200	.225	3.23	203.5	19.3	2.38
Minimum Thickness Guidelines			.209	.167				
Satisfy Strength Requirement	NC	NC	.188*	.188"	2.94	183.4	17.1	2.23
percent increase (decrease)			(6.0%)	(16.4%)	(9.0%)	(9.9%)	(11.4%)	(6.3%)
Match Strength of Original	NC	NC	.188"	.25	3.18	209.0	19.8	2.23
percent increase (decrease)			(6.0%)	11.1%	(1.5%)	2.7%	2.6%	(6.3%)

2ND PLATFORM DECK STIFFENER (COMPARTMENT 3-220-01-A)
(Located below the ship's vertical center of gravity)

CONFIGURATION	D(in)	WF(in)	TW(in)	TF(in)	$A_{stiff}(in^2)$	$I(in^4)$	$SM_{flg}(in^3)$	$A_{shear}(in^2)$
8 X 4 X 10# I-T w/.3l3" plate	7.89	3.94	.170	.205	2.11	59.0	9.2	1.34
Minimum Thickness Guidelines			.135	.165				
Satisfy Strength Requirement	NC	NC	.1345*	.1644*	1.69	49.8		1.06
percent increase (decrease)			(20.9%)	(19.8%)	(19.9%)	(15.6%)	(18.5%)	(20.9%)
Match Strength of Original	NC	NC	.1345*	.25	2.02	62.6	9.9	
percent increase (decrease)			(20.9%)	22.0%	(4.3%)	6.1%	7.6%	(20.9%)

01 LEVEL WEATHER DECK STIFFENER NEAR SHELL AT FRAME 276
(Located below the ship's vertical center of gravity)

CONFIGURATION	D(in)	WF(in)	TW(in)	TF(in)	$A_{stiff}(in^2)$	$I(in^4)$	$SM_{flg}(in^3)$	$A_{shear}(in^2)$
6 X 4 X 9# I-T w/.50 plate	5.90	3.94	.170	.215	1.81	37.2	6.8	1.34
Minimum Thickness Guidelines			.099	.165				
Satisfy Strength Requirement	NC	NC	.1046	.25		37.7	6.9	0.62
percent increase (decrease)			(38.5%)	16.3%	(12.7%)	1 .3%	1 .5%	(53.7%)
Match Strength of Original	NC	NC	.1046	.25	1.58	37.7	6.9	0.62
percent increase (decrease)			(38.5%)	16.3%	(12.7%)	1 .3%	1 .5%	(53.7%)

Table 4. Tabulated Results of Plate Stiffener evaluation

TRANSVERSE BULKHEAD STIFFENER (FRAME 174) BETWEEN INNERBOTTOM AND 2ND PLATFORM
(Located below the ship's vertical center of gravity)

CONFIGURATION	D(in)	WF(in)	TW(in)	TF(in)	A_{stiff}(in^2)	I(in^4)	SM_{flg}(in^3)	A_{shear}(in^2)
12 X 4 X 14# I-T w/.3l3" plate	11.91	3.97	.200	.225	3.23	163.2	18.1	2.38
Minimum Thickness Guidelines			.209	.167				
Satisfy Strength Requirement	NC	NC	.1644"	.25		162.1	17.9	1.96
percent increase (decrease)			(17.7%)	11.1%	(10.2%)	(0.7%)	(1.1%)	(17.7%)
Match Strength of Original	NC	NC	.1644"	.313	3.15	180.0	20.4	1.96
percent increase (decrease)			(17.7%)	38.9%	(2.5%)	10.3	12.8.	(17.7%)

TRANSVERSE BULKHEAD STIFFENER (FRAME 174) BETWEEN 2ND AND 1ST PLATFORMS
(Located below the ship's vertical center of gravity)

CONFIGURATION	D(in)	WF(in)	TW(in)	TF(in)	A_{stiff}(in^2)	I(in^4)	SM_{flg}(in^3)	A_{shear}(in^2)
10 x 4 x 12# I-T w/l88" plate	9.87	3.96	.190	.210	2.67	72.5	11.9	1.88
Minimum Thickness Guidelines			.172	.166				
Satisfy Strength Requirement	NC	NC	.1644	.188	2.33	67.2	10.8	1.62
percent increase (decrease)			(13.8%)	(10.5%)	(12.7%)	(7.3%)	(9.2%)	(13.8%)
Match Strength of Original	NC	NC	.1644	.25	2.57	75.4	12.7	1.62
percent increase (decrease)			(13.8%)	19.0%	(13.7%)	4.0%	7.0%	(13.8%)

TRANSVERSE BULKHEAD STIFFENER (FRAME 174) BETWEEN IST PLATFORM AND MAIN DECK
(Located above the ship's verticaf center of gravity)

CONFIGURATION	D(in)	WF(in)	TW(in)	TF(in)	A_{stiff}(in^2)	I(in^4)	SM_{flg}(in^3)	A_{shear}(in^2)
8 X 4 X 10# I-T w/.156' plate	7.89	3.94	.170	.205	2.11	37.0	8.2	1.34
Minimum Thickness Guidelines			.135	.165				
Satisfy Strength Requirement	NC	NC	.1196"	.1644"	1.57	31.8	6.6	0.94
percent increase (decrease)			(29.6%)	(19.8%)	(25.6%)	(14.1%)	(19.8%)	(29.6%)
Match Strength of Original	NC	NC	.1345	.25	2.02	38.6	8.9	1.06
percent increase (decrease)			(20.9%)	22.0%	(4.3%)	4.3%	8.5%	(20.9%)

Table 4- Cont. Tabulated Results of Plate Stiffener Evaluation

TRANSVERSE BULKHEAD STIFFENER (FRAME 174) BETWEEN MAIN DECK AND 01 LEVEL
(Located above the ship's vertical center of gravity)

CONFIGURATION	D(in)	WF(in)	TW(in)	TF(in)	$A_{stiff}(in^2)$	$I(in^4)$	$SM_{flg}(in^3)$	$A_{shear}(in^2)$
5 X 4 X 6# I-T w/.l56" plate	4.94	3.96	.190	.210	1.73	13.7	4.8	0.94
Minimum Thickness Guidelines			.080	.166				
Satisfy Strength Requirement	NC	NC	.1046	.1644"	1.15	11.5	3.7	0.52
percent increase (decrease)			(44.7%)	(21.7%)	(33.5%)	(16.1%)	(23.8%)	(44.7%)
Match Strength of Original	NC	NC	.1196	.25	1.55	14.1	5.1	0.59
percent increase (decrease)			(37.2%)	19.0)%	(10.4%\	3.1%	5.8%	(37.2%)

•Note In some cases the web and or flange thickness selected for the welded tee section falls slightly under the guideline value. In these instances the calculated web shear values are considerably lower that the allowable values, relieving the danger of failure due to instability. And similarly, calculated compressive stresses in the flanges are sufficiently low to assure flange stability.

Table 4- Cont. Tabulated Results of Plate Stiffener Evaluation

RESULTS OF EVALUATION - Continued

The relatively small set of data and the range of weight savings indicated limits the extent of the conclusions and follow work which can be based on these figures. However, conservative estimates of overall weight savings and the impact of reduced stiffener area on the ship's longitudinal strength can be made with confidence. For purposes of estimating savings, the evaluation method based on satisfying strength requirements will yield the most accurate results while the evaluation method which matches the strength of the current section will provide a conservative boundary.

Potential Overall Weight Savings for a DDG 51 Class Ship - A review of the results for welded Tees sized to satisfy the calculated strength requirements shows that the minimum indicated stiffener area savings is 9%. In light of an average indicated stiffener savings of 18%, calculated weight savings based on a 9% reduction will yield a conservative result.

Table 5 offers a summary of the stripped stiffeners used for a single DDG 51 ship, calculated welded Tee potential weight savings for each stiffener type and a total potential stiffener weight savings per ship of more than 46 long tons. Insufficient data is available and development is beyond the scope of this evaluation to assess the overall impact of this potential weight reduction on the ship's VCG.

RESULTS OF EVALUATION - Continued

Table 5 also summarizes the calculated weight of scrap material generated by the currently used stripping process. In addition to the material saved by stiffener area reduction possible with welded Tees, more than 170 long tons of generated scrap material could be eliminated.

Wide Flange Section (lbs/ft)	Bar Length (ft)	Quantity of Bars per Hull	Total Bar Length per Hull (ft)	T Section Weight (lbs/ft)	9% of T Section Wt. (lbs/ft)	Welded T Section Wt. Savings (lbs)	Stripping Scrap (lbs/ft)	Stripping Scrap (lbs)
W6 x 9	49	195	9,555	6.43	0.58	5,529	2.57	24,556
W8 x 10	40	2	80	7.48	0.67	54	2.52	202
W8 x 10	49	319	15,631	7.48	0.67	10,523	2.52	39,390
W8 x 13	49	67	3,283	9.90	0.89	2,925	3.10	10,177
W8 x 18	20	25	500	12.92	1.16	581	5.08	2,540
W10 x 12	49	154	7,546	9.49	0.85	6,445	2.51	18,940
W10 x 15	40	17	680	11.64	1.05	712	3.36	2,285
W10 x 17	40	25	1,000	12.89	1.16	1,160	4.11	4,110
W10 x 19	49	15	735	14.24	1.28	942	4.76	3,499
W12 x 14	49	216	10,584	11.27	1.01	10,735	2.73	28,894
W12 x 16	49	139	6,811	12.83	1.15	7,865	3.17	21,591
W12 x 19	49	10	490	14.81	1.33	653	4.19	2,053
W12 x 22	49	46	2,254	16.78	1.51	3,404	5.22	11,766
W12 x 26	49	47	2,303	18.24	1.64	3,781	7.76	17,871
W12 x 30	49	24	1,176	21.00	1.89	2,223	9.00	10,584
W12 x 50	49	8	392	33.25	2.99	1,173	16.75	6,566
W14 x 22	49	56	2,744	16.85	1.52	4,161	5.15	14,132
W14 x 26	49	64	3,136	19.54	1.76	5,515	6.46	20,259
W14 x 34	49	21	1,029	24.21	2.18	2,242	9.79	10,074
W14 x 43	49	24	1,176	29.11	2.62	3,081	13.89	16,335
W16 x 26	49	28	1,372	20.13	1.81	2,486	5.87	8,054
W16 x 31	49	25	1,225	23.53	2.12	2,594	7.47	9,151
W16 x 36	49	10	490	26.44	2.38	1,166	9.56	4,684
W16 x 40	49	9	441	28.82	2.59	1,144	11.18	4,930
W16 x 45	49	2	98	32.47	2.92	286	12.53	1,228
W16 x 50	49	14	686	36.03	3.24	2,224	13.97	9,583
W18 x 35	49	35	1,715	27.12	2.44	4,186	7.88	13,514
W18 x 40	49	42	2,058	30.27	2.72	5,607	9.73	20,024
W18 x 50	49	46	2,254	36.48	3.28	7,400	13.52	30,474
W18 x 60	49	13	637	43.51	3.92	2,494	16.49	10,504
W24 x 55	20	18	360	44.18	3.98	1,431	10.82	3,895

Total Potential Stiffener Weight Savings Using Welded Tees **104,722 Lbs**

Total Potential Stiffener Weight Savings Using Welded Tees **46.75 L. Tons**

Total Potential Scrap Weight Reduction Using Welded Tees **381,865 Lbs**

Total Potential Scrap Weight Reduction Using Welded Tees **170.48 L. Tons**

Table 5. Potential Overall Weight and Material Savings on DDG 51 Class Ships Assuming a 9% reduction in stiffener area and savings of currently scrapped flanges stripped from wide flange shapes to make Tees.

RESULTS OF EVALUATION - Continued

Stiffener Area Reduction In Transverse Bulkheads - The range of indicated stiffener area savings in the results is too great to state with confidence that more or less potential for relative savings exists in transverse bulkheads over other locations or applications. Confidence in the trends seen in the results could be strengthened by increasing the number of stiffened panels investigated.

Where welded Tees were sized to satisfy the bending strength requirements, the results show some indication that the potential for stiffener area relative savings may be higher for the stiffeners in transverse bulkheads than for longitudinal structural stiffeners. Stronger evidence can be found in the results to show that the potential for relative area savings in transverse bulkhead stiffeners is greater above than below the ship's VCG. It should be noted here, however, that because transverse bulkhead stiffener area tends to decrease as you move upward in the ship, higher relative area savings will not necessarily translate into a net area or weight savings.

Effect of Stiffener Area Reduction on Ship Longitudinal Strength - Reducing the area of longitudinal stiffeners in the hull girder through the use of welded Tees will lower slightly the longitudinal strength properties of the ship. The anticipated effect of the reductions in stiffener properties indicated by this evaluation on the hull girder longitudimd strength properties are outlined in table 6. Existing hull girder strength properties are drawn from reference 9.

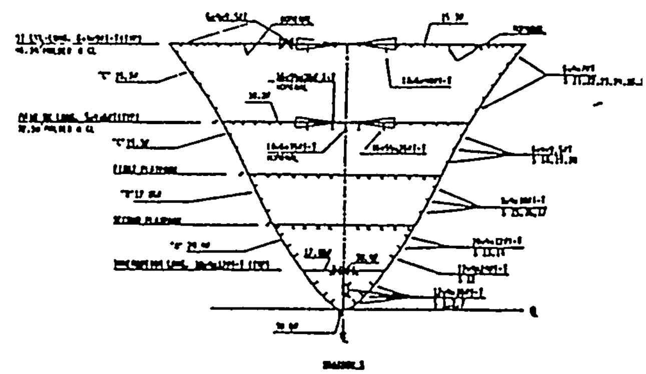
The evaluation at DDG 51 station 3 (frame 70) shows a reduction of section inertia of 2.1%. It is reasonable to expect a reduction of this order at each of the other calculation stations throughout the hull.

Current strength margins for the DDG 51 Class are adequate to accommodate this reduction in hull girder strength properties. The DDG 51 longitudinal strength drawing (reference 9) shows that the strength margin available is no less than 9% at any point along the length of the hull with the minimum margin found at station 14 (frame 326).

RESULTS OF EVALUATION - Continued

ANTICIPATED REDUCTION IN STIFFENER PROPERTIES

Shell Stiffeners		
Area	9%	
Inertia	15%	(estimated)
Section Modulus	16%	(estimated)
Deck Stiffeners		
Area	16%	
Inertia	15%	(estimated)
Section Modulus	16%	(estimated)



FROM DDG 51 LONGITUDINAL STRENGTH CALCULATIONS - STATION 3 (FRAME 70)

	Area	Ix	Ad^2
Shell	425.64	155.43	88,776
Decks	531.90	0.10	241,415
Shell Stringers	81.24	0.68	16,741
Deck Longitudinals	117.32	12.94	41,406
	1156.10	169.15	388,338

Total Section Inertia = $\Sigma Ix + \Sigma Ad^2$ = 388,508 $in^2\ ft^2$

IF STIFFENER AREA AND INERTIA IS REDUCED OVERALL BY ABOVE FACTORS

	Area	Ix	Ad^2
Shell	425.64	155.43	88,776
Decks	531.90	0.10	241,415
Shell Stringers	81.24	0.68	16,741
	- 7.31	- 0.11	- 1,507
Deck Longitudinals	117.32	12.94	41,406
	- 18.77	- 2.07	- 6,625
	1130.02	166.97	380,206

Total Section Inertia = 380,206 $in^2\ ft^2$ (2.1% reduction)
Total Area = 1130.02 in^2 (2.3% reduction)

Table 6. Hull Girder Longitudinal Strength Evaluation

REFERENCES

1. Specifications for Building Guided Missile Destroyer DDG 51.

2. U.S. Navy Design Data Sheet (DDS) 100-3; Structural Design of Flat Plating Subject to Water Pressure; 17 November 1955.

3. U.S. Navy Design Data Sheet (DDS) 100-4; Strength of Structural Members; 15 November 1982.

4. U.S. Navy Design Data Sheet (DDS) 100-6; Longitudinal Strength Calculation; 29 May 1987.

5. NAVSEA Publication O9OO-LP-O97-4O1O; Structural Design Manual for Naval Surface Ships; 15 December 1976.

6. MIL-HDBK-264(SH); Properties of Steel Shapes and Plate Beam Combination Used in Shipbuilding; 30 September 1980.

7. Manual of Steel Construction - Allowable Stress Design; American Institute of Steel Construction, Inc. (AISC); Ninth Edition; 1989.

8. Steel Structures Design and Behavior; Salmon and Johnson; Harper & Row, Publishers; 1971.

9. BIW Dwg. No. 0450-KS-0802-01; DDG 51 Class Longitudinal Strength and Inertia Sections.

10 BIW Calculation No. 8825-100-0001; Engineering Evaluation of Welded Tees vs. Stripped Tees in Stiffened Panels; dated 7/15/92.

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